Performance Improvement of the 2-Mass Rotary System via Adaptive Tabu Search

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Abstract: - A 2-mass rotary system is widely used in industrial applications. Torsional resonance, however, usually appears in such the system. This article presents an attempt to suppress torsional resonance and to improve the performance of a system. With two-degree-of-freedom (2-DOF) configuration, feedforward and feedback compensators are used. The former provides desired performance of the system, while the latter suppresses resonance. The design approach is transfer function synthesis based on pole-zero assignment. Moreover, to gain better performance of the overall system, the adaptive tabu search (ATS) method, one of the AI search techniques, is applied. The satisfactory response has been achieved without torsional resonance.

Key-Words: - 2-mass rotary system, torsional resonance, pole-zero assignment, adaptive tabu search.

1 Introduction

A mechanical system with physical structure rendering torsional resonance is commonly encountered in industry, for example material transporting systems, xy plotters, and robots, etc. A 2-mass rotary system having its rotating components coupled by a long and deflective shaft usually experiences torsional resonance. This phenomenon arises because of the non-homogeneous twist of the shaft. The resonance causes a limit-cycle oscillation to angular motion of the system, and shortens the life-span of mechanical components.

Over four decades, the problem of torsional resonance has become an interest among engineers. This is evident by Cannon [1] who discussed it in terms of modelling of distributed parameter system. Early solutions to the problem of torsional resonance suppression were proposed by Waagen [2], Tal and Kuo [3], respectively. Their recommendations were quite similar on the basis of modification of mechanical characteristics of the system. The modification could be changing components’ dimension, and rearranging the connection of subsystems. Tal and Kuo [3] also observed the possibility of using a notch filter to reject frequency component that might excite the resonance.

Recently, several proposed approaches to resolve the problem have become more complex and expensive. Fujikawa et. al. [4] employed a 32-bit DSP to execute state-space control law. H∞ approach with an additional adaptive loop was proposed [5]. Torsional vibration suppression by using state feedback speed controller and by LQG based speed controller were proposed in [6] and [7], respectively. Estimation of load speed and shaft torque by Kalman filter, and speed governing by an LQ controller were proposed in [8]. All these approaches need a high performance processor to realize controller and/or observer.

Nowadays, some AI search techniques such as genetic algorithm (GA) and tabu search (TS) have been accepted and used in industrial control applications. By literature, the adaptive tabu search (ATS) method is an alternative, which has global convergence property [9]. Interestingly, it requires less time consumed, comparative to that spent by the GA [10]. In addition, the ATS method has been extended to linear and nonlinear identifications of some complex systems [11], and to controller designs for higher-order plants [12].
This article proposes an approach to resolve the problem of torsional resonance suppression in a 2-mass rotary system with a long and deflective shaft by using feedforward and feedback compensators. The overall system performance is further improved via the ATS method. This article consists of five sections. Section 2 describes a 2-mass rotary system and its model. A design of 2-DOF system structure is described in Section 3. Performance improvement via the ATS method is explained in Section 4, while Section 5 gives the conclusions. Simulation results confirm the attainment of the proposed approach.

2 System and Modelling

A 2-mass rotary system is illustrated in Figure 1, while the block diagram of such the system is represented in Figure 2.

\[ G(s) = \frac{1.32 \times 10^6}{s^3 + 13.38s^2 + 1.63 \times 10^5 s + 7.31 \times 10^5} \]  

Fig. 3 Step response plots.

Fig. 4 Frequency response plot.

\[ \omega_n = 2\pi f_{\text{resonant}} = \sqrt{\frac{K_{sh}}{J_m + \frac{1}{J_l}}} \]  

\[ \omega_z = \frac{K_{sh}}{\sqrt{J_l}} \]  

The mechanical resonant frequency, \( \omega_n \), and the anti-resonance frequency, \( \omega_z \), as shown in (1) and (2), respectively, are the important characteristics of a 2-mass system.

Linear operating range of the system is assumed throughout this work. Motor and load assume second-order dynamics, whereas first-order for shaft with coupling. Naturally, this leads to a third-order transfer function having a pair of complex conjugate poles. To conduct system identification, observed data were obtained from exciting the open-loop system with a step input. MATLAB\textsuperscript{TM} and a system identification toolbox have been used to fit a third-order model [13, 14]. The model assumes no zero and is expressed by (3).

Fig. 1 A 2-mass rotary system.

Fig. 2 Block diagram of a 2-mass rotary system.

\[ \begin{align*}
\omega_m &= \text{angular speed of the motor,} \\
\omega_h &= \text{angular speed of the load,} \\
J_m &= \text{moment of inertia of the motor,} \\
J_l &= \text{moment of inertia of the load,} \\
T_m &= \text{motor torque,} \\
T_l &= \text{load torque,} \\
T_{sh} &= \text{shaft torque,} \\
\theta_{sh} &= \text{angular displacement of the shaft,} \\
K_{sh} &= \text{stiffness of the shaft}
\end{align*} \]
3 Design of 2-DOF System Structure

In this work, transfer function synthesis with pole-zero assignment method was used to suppress torsional resonance. As 2-degrees-of-freedom (2-DOF) configuration, theoretically, the achieved system consists of a plant and two compensators as shown by the block diagram in Figure 5. The feedback compensator, \( G_{fb}(s) \), helps to eliminate oscillation due to resonance and stabilize the feedback loop, while the feedforward or input compensator, \( G_{ff}(s) \), helps the system to achieve satisfactory response. Pole-zero assignment technique \[15, 16\] was used to design the proposed control system structure.

\[ G_{ff}(s) = \frac{15.09(s^2 + 4 \times 10^5 s + 4 \times 10^6)(s+2000)}{10000(s^2 + 7.19 \times 10^5 s + 19.16 \times 10^6)} \]  
\[ G_{fb}(s) = \frac{16.83(s^2 + 2.71 \times 10^5 s + 5.04 \times 10^5)(s+142.36)}{s(s^2 + 7.19 \times 10^3 s + 19.16 \times 10^6)} \]

Figure 6 shows the simulated response when the 2-mass rotary system is compensated by the proposed compensation scheme. Limit-cycle oscillation is completely eliminated, and a fast response can be achieved. In Figure 6, the response shows the percent overshoot (P.O.) of 4 and no steady-state error. The rise time (\( T_r \)) and the settling time (\( T_s \)) are 20 ms and 70 ms, respectively. Figure 7 shows frequency response of the compensated system. The bandwidth of the compensated system is about 150 rad/sec.

4 Performance Improvement via ATS

To improve the performance of the overall system, the adaptive tabu search (ATS) method \[9\] is applied. Details of the ATS are briefly explained in the Appendix. Regarding to the optimization context, both feedforward, \( G_{ff}(s) \), and feedback, \( G_{fb}(s) \), compensators could be optimized by the ATS to gain better response as shown in Figure 8, where \( R(s) \) and \( C(s) \) are the reference response and the actual response, respectively. The cost function, \( J \), the sum-squared error (\( E_{ss} \)) between \( R(s) \) and \( C(s) \) as stated in (6), is fed back to the ATS block and therefore minimized to obtain optimum parameters of both compensators. The desired specifications are given by \( T_r \leq 15 \text{ ms} \), \( P.O. \leq 5\% \), \( T_s \leq 40 \text{ ms} \), and \( E_{ss} \leq 0.001 \) set as inequality constraint as expressed in (7).

\[ J = \sum |R(s) - C(s)|^2 \]  
\[ \text{Minimize} \quad J \]  
\[ \text{Subject to} \quad T_r \leq 15 \text{ ms} \]  
\[ P.O. \leq 5\% \]  
\[ T_s \leq 40 \text{ ms} \]  
\[ E_{ss} \leq 0.001 \]
The ATS-based optimization is summarized as follows. The back-tracking mechanism is activated when $MAX\_cycling$ (maximum cycling allowance) $= 10$. The adaptive-radius mechanism is used as well. In each search round, 40 neighborhood members are randomly generated and $MAX\_count$ is set as 1000. After the searching process stopped, the ATS provided the solutions with $J = 4.02 \times 10^2$, search rounds of 452, and consumed 28.21 seconds of search time. Both search rounds of 452, and consumed 28.21 seconds of search time. Both $G_f(s)$ and $G_{fb}(s)$ are successfully obtained as stated in (8) and (9), respectively. The step and the frequency responses of the system before and after improvement are shown in Figure 9 and Figure 10, respectively. As the simulation results, the performance of a 2-mass rotary system after improvement by the ATS provides superior results.

5 Conclusions
Torsional resonance suppression in a 2-mass rotary system by transfer function synthesis with pole-zero assignment method has been proposed in this article. With 2-DOF control system structure, torsional resonance is completely suppressed. The ATS method is applied to gain better performance of the overall system. As the simulation results, the performance of a 2-mass rotary system after improvement by the ATS provides superior results than before.

6 Appendix: The ATS Method
The ATS method [9] is one of the efficient AI search techniques. It is based on iterative neighborhood search approach. The tabu list (TL) having first-in-last-out property is used to record a history of solution movements which may lead to a new direction that could escape a local minimum trap. In addition, the ATS method has two additional mechanisms, namely back-tracking and adaptive-radius, to enhance its convergence. The ATS algorithm is summarized, step-by-step, as follows.

1) Initialize a search space, $count$ and $MAX\_count$.
2) Randomly select an initial solution $x_0$ from a search space. Let $x_0$ be a current local minimum.
3) Randomly generate $N$ solutions around $x_0$ within a certain radius $R$. Store the $N$ solutions, say neighborhood, in a set $X$.
4) Evaluate a cost function of each member in $X$. Set $x'$ as a member that gives the minimum cost in $X$.
5) If \( x' < x_0 \), put \( x_0 \) into the TL and set \( x_0 = x' \), otherwise, store \( x' \) in the TL instead.

6) Activate the back-tracking mechanism, when solution cycling occurs.

7) If the termination criteria: \( \text{count} \geq \text{MAX\_count} \) (maximum search round), or desired specifications are met, then stop the search process. The solution \( x_0 \) is the best solution (global minimum), otherwise go to 8.

8) Activate the adaptive-radius mechanism, when a current solution \( x_0 \) is closed to a local minimum to refine searching accuracy.

9) Update \( \text{count} \), and go to 2.

The back-tracking mechanism is activated when the number of solution cycling is equal to the maximum solution-cycling allowance. This mechanism selects an already visited solution stored in the TL as an initial solution for the next search round to enable a new search path that could escape the local deadlock towards a new local minimum. For the adaptive-radius mechanism, it is invoked when a current solution is relatively close to a local minimum. The radius is thus decreased in accordance with the best cost function found. The less the cost function, the smaller the radius. With these two features, a sequence of solutions obtained by the ATS method rapidly converges to the global minimum. Convergence analysis and performance evaluation of the ATS method can be found in [9].

References: