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A turboshaft engine NMPC scheme for helicopter autorotation recovery maneuver

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ABSTRACT

Fast response for turboshaft engine plays an important role in shaping sound helicopter maneuver ability during some typical violent maneuvers like autorotation power recovery. An engine NMPC (nonlinear model predictive control), integrated with flight predictive information, is proposed to obtains better engine response speed and reduces the rotor transient droop during autorotation power recovery. The on-board nonlinear predictive model consists of two parts: one is "load" model – a main rotor torque model, the other is a turboshaft engine model. A suitable objective function is specified for the NMPC algorithm, being related to the deviation between the torque provided by the power turbine and that demanded by helicopter. The smaller torque deviation when its clutch being connected is, the less main rotor speed droop is. Finally, comparison simulations with a popular H_2/H_∞ robust control are demonstrated. It shows that by using the NMPC control law proposed here, the main rotor speed droop is only 0.36% with respect to reference speed, whereas it is 2.3% when using the robust control. Moreover, the designed control law is able to shorten the stable time a lot during the process, as the stable time is about 5 s when employing the new scheme, while it is about 20 s for the robust control.

1. Introduction

Along with the development in aviation science and technology, the reliability of engine equipment in helicopter has been enhanced a lot. However, some flight accident statistics show that engine failures still account for the main reason of all aircraft accidents [1–3]. Autorotation of a helicopter makes use of the potential energy to maintain the main rotor speed constant, so the main rotor thrust can be controlled to operate the helicopter within a safe landing velocity. Also, it is one of most important maneuvers to quickly bop up and bop down in combats. Thus, during emergency situation, especially when turbo-shaft engine blows out, prompt and accurate autorotation control ensures helicopter lands safely and has much bigger survival probability. Therefore, autorotation performance is an important indicator of helicopter airworthy [2].

A typical autorotation mainly consists of following phases: turboshaft engine failure, autorotation entry, descent flight, steady (trimmed) autorotation and finally power recovery from the autorotation, as shown in Fig. 1. In the first phase, the rotor shaft is disengaged from the power turbine shaft by a clutch, whereas for training the engine does not really enter into malfunction but into an idle state. Next, in the autorotation's entry phase, the main rotor collective angle is immediately lowered to prevent main rotor speed from sudden decreasing and to provide enough rotor thrust to achieve a steady descent rate. Subsequently, if being successful the helicopter will enter into a steady (trimmed) autorotation phase at a certain descent rate where the rotor speed slightly changed. Finally, the recovery from the autorotation involves main rotor collective flare from the pilot, therefore, the clutch are connected again when the rotor and the gear box output shaft speed remains within a small range. Whether in autorotation training or combat autorotation maneuver, fast response for turboshaft engines do a lot contribution for sound maneuver ability, especially during autorotation power recovery stage [3].

Autorotation power recovery control has been investigated as a typical integrated flight and engine control in literatures, and the word "integrated" herein means that an turboshaft engine control design should consider load changes from the helicopter. An integrated control system for AH-64 helicopter/T700 engine system were studied by Shanthakumaran [3]. The simulations showed that when the increasing rate of main rotor collective pitch is 29%, the power turbine speed or the main rotor speed would droop by 5%,

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Nomenclature

W_f	Fuel flow	(kg/s)
α_c	Compressor guide vanes angle (CGV)	(°)
N_g	Gas turbine speed	(%)
N_p	Power turbine speed	(%)
S_{mc}	Compressor surge margin	(%)
T_4	Turbine inlet temperature	(°C)
N_m	Main rotor speed	(%)
Q_H	Main rotor torque	(N m)
Q_E	Turbo-shaft engine torque	(N m)
H	Helicopter altitude	(m)
V_z	Helicopter climb speed	(m/s)
V_x	Helicopter forward flight speed	(m/s)
V_y	Helicopter side flight speed	(m/s)
θ_0	Collective pitch of the main rotor	(°)
A_{1c}	Lateral cyclic pitch of the main rotor	(°)
B_{1s}	Longitudinal cyclic pitch of the main rotor	(°)

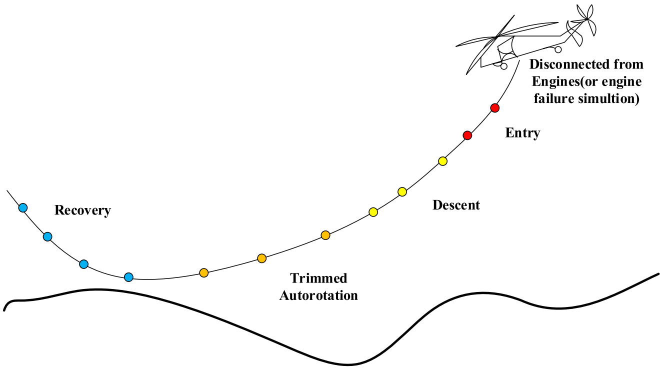

Fig. 1. Autorotation process.

and when the rate turned to be 35%, the rotor speed would droop by 12%. A big droop reflects that the engine power cannot provide prompt power to the main rotor. So, how to suppress the main rotor speed droop is a key for engine control design during helicopter maneuvers. For decreasing main rotor speed droop and enhancing helicopter responsibility, the U.S. army developed an integrated flight and engine control for the Sikorsky Black Hawk helicopter, which is equipped with Pratt and Whitney 3000SHP turboshaft engines [4,5], and the control adopted an online PNN (probabilistic neural network) model to predict main rotor dynamic torque as feed forward compensation.

Almost at the same time in Europe, the project IFEC (integrated flight and engine control) and APSEC (advanced power system engine control) were initialed [6]. The project APSEC firstly employed compressor guide vane angle to improve engine response ability and decrease main rotor speed droop. Moreover, advanced control schemes for improving system responsibility were deeply investigated. A cascade PID method combined with torque feed forward compensation ADRC (active disturbance rejection control) was developed in literatures [7–9]. And Refs. [10,11] devised another cascade PID control with a torque prediction module, which is based on recursive reduced least squares support vector regression method. Also, some researchers began to apply modern robust methods to engine control for autorotation [12–16], especially in Refs. [15,16], a H_2/H_∞ robust control was designed regarding the torque as disturbance, the main rotor transient droop being reduced to 3% whereas more than 5% for traditional controls.

For a typical autorotation, especially in autorotation recovery, extremely large and rapid change of main rotor torque or "loading" to engines is inevitable on emerging. This transient process is strongly nonlinear. Due to combined working of main rotor, airframe, engine and mechanical transition system, the couple dynamics effect among them is very complicated. Moreover, during autorotation recovery process, there exists unneglectable control delay between "loading" and engine output, which caused by large moment of rotor inertia and sensor time lag. In maneuvering flight with short time length, control delay must be taken into consideration. Due to the lack of prediction for time lag, the conventional control methods, like PID or other robust control H_2/H_∞, do not perform well in controlling time lag.

MPC (model predictive control) [17], for its prediction ability, it is an alternative scheme to solve nonlinear system control problem with time delay. Since 1990s, linear MPC has achieved significant developments in theory and application [17–19], such as dynamic matrix control [20], generalized predictive control [21] and etc. It is capable of solving constraint optimization problem real-timely and dynamically programming [22]. In recent years, some new MPC methods, such as robust MPC [23] and NMPC (nonlinear model predictive control), have been proposed. These methods can be used to effectively solve nonlinear system control problems with complex constraints and disturbances. Hence, many researches have be aroused great interest in the implement of MPC to helicopter control. The GPC (Generalized Predictive Control) controller is applied to control a helicopter model in document [24]. A method which based on a combination of a neural network feedback controller and a state-dependent Riccati equation controller is present and applied to a 6 degree of freedom (DOF) model of an autonomous helicopter [25]. The MPC is used to trajectory track of an unmanned quadrotor helicopter subject to aerodynamic disturbances [26]. Document [27] proved that constrained MPC can be used and implemented online to robustly track discontinuous helicopter trajectories with heterogeneous constraint. The MPC is applied to helicopter shipboard operations in the presence of ship airwakes and rough seas [28]. In 2007, Glenn Research Center of American National Aeronautics and Space Administration held an important meeting about intelligent aero-engine [29], and the concept of a NMPC for integrated propulsion and flight system was firstly recommended for being highly effective in online nonlinear optimization problem with time-delay. Through some NMPC studies found in helicopter control [24–28] and turbofan engine control [30–32], almost no investigations using NMPC have been implemented for autorotation recovery process.

Therefore, an engine NMPC, which can predictively control the working profile of a turbo-shaft engine and its load variation, is proposed for autorotation power recovery process, with fuel flow and compressor guided vanes angle being control variables. As per NMPC, the key problem is to devise an online model for turbo-shaft engine and its load from main rotor. Based on the MRR-LSSVR (multi-input multi-output recursive reduced least squares support vector regression) [33,37] algorithm, a main rotor torque predictive model for predicting the load from main rotor and a turbo-shaft engine predictive model are developed respectively as the online predictive models. The online optimization objective function includes two parts: One is to limit the difference between the torque provided by the power turbine and the main rotor, and the other is to maintain the power turbine speed always close to 100%. What's more, necessary engine operation constraints, as the maximum fuel growth rate and the highest turbine inlet temperature, are taken into consideration. Naturally, the problem is transformed to a NMPC problem. And the FSQP (feasibility sequence quadratic