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# Longitudinal Attitude Controller Design for Aircraft Landing with Disturbance Using ADRC/LQR

Guilong Zhang, Lingyu Yang, Jing Zhang, Chan Han

**Abstract**—In this paper, a control method combining Active Disturbance Rejection Control (ADRC) and optimal control is discussed for large aircraft landing attitude control with disturbances, such as turbulence, gusts and modeling errors. On the basis of the extended state observer (ESO) inherited from ADRC, our design exploits the Linear Quadratic Regular (LQR) replacing the original Proportional-Derivation (PD) gains. This technique can effectively solve the adjustment problems of the former channel parameters in ADRC, and can guarantee the unknown disturbance rejection at the same time. Simulation of the B747 longitudinal nonlinear model is represented to test the method. Results show that this method offers satisfying effects. The design proposed in this paper is superior to LQR in terms of disturbance rejection, and has a better performance than ADRC in the aspects of dynamic behavior.

## I. INTRODUCTION

The aircraft landing is the most dangerous stage of a flight. A 2012 Boeing Statistical Summary of Jet Airplane Accidents [1] showed that fatal accidents in the final approach and landing accounted for 37% for the entire flight phase during the last decade. Atmospheric turbulence, gusts and wind shear have a serious impact on the aircraft landing process and affect the attitude and tracking accuracy of the aircraft. According to Federal Aviation Administration (FAA) regulations [2], the maximum allowable wind speeds, when conducting a dual channel CAT II or CAT III landing predicated on auto land operations, are headwinds of up to 25 knots, crosswinds of up to 25 knots, and tailwinds of up to 10 knots. Taking potential modeling error into account, the aircraft controller design should consider greater disturbance than the above-described circumstances. The controller for this stage requires not only good dynamic behavior but also a greater resistance to disturbances, including outside interference and the internal system modeling error. In short, auto landing control systems need higher requirements.

Active Disturbance Rejection Control (ADRC) technology was proposed in 1998 by Jingqing Han [3], and first introduced in English by Z. Gao [4]. Its core idea is to estimate the unknown internal and external disturbances as one signal by using an extended state observer, and then to impart the signal to the control law. This allows the controller to have ample means of curbing the unknown interference. In

the field of aerospace, a wide range of ADRC applications can be found in [5]-[7] and are referenced therein.

ADRC technology consists of a tracking differentiator, an extended state observer and an error-based control law. There are a considerable number of parameters to be set in the nonlinear functions of this technique. In recent years, a new form of ADRC control technology was developed in [8]. When the error-based law applies the proportional-derivation, its parameters adjustment requires experienced engineering. There is no general way of tuning the parameters in order to contribute to a fast response, a small overshoot and no steady-state error dynamics behavior on nonlinear systems. The parameters settings tend to be more cumbersome and diminish the ability of the system to achieve an optimum performance. The LQR controller can solve the optimal control input signal for a certain quadratic indicator. Its excellent control performance has made it a favorite among control engineers. The design process is not very complex as a result of choosing certain control indicators and tuning the weighing values. In this paper, we extended ADRC in [8] using LQR.

This paper presents a longitudinal attitude controller, aimed at resisting severe disturbance during landing. In accordance with the requirements of flight dynamic characteristics, we replaced the PD gains in ADRC with LQR into a developed controller. The B747 nonlinear longitudinal model was tested to compare the ADRC/LQR, the linear ADRC and LQR methods. The results showed that with severe wind interference and model uncertainty, the ADRC technique can adopt unknown disturbance, and its dynamic characteristics are ideal.

The remainder of this article is arranged as follows. Section II describes the model of the aircraft. In Section III, a developed ADRC law is represented, including the linear ESO design and LQR controller design. The simulation results and conclusion can be found in Section IV and Section V.

## II. MODEL OF THE AIRCRAFT

We took the B747 nonlinear model as a prototype to design a longitudinal landing attitude controller. The data were taken from *The Simulation of a Jumbo Jet Transport Aircraft Volume II: Modeling Data* [9] by C. Roney Hanke et al.. In this paper, only the longitudinal motion was considered as shown in Fig. 1. The equations of motion of the longitudinal dynamics [10] are described as:

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$$\begin{cases} m\dot{V} = T \cos \alpha - D - mg \sin(\theta - \alpha) \\ mV\dot{\gamma} = T \sin \alpha + L - mg \cos(\theta - \alpha) \\ I_y \dot{q} = M^a + Tz_T \\ \dot{\theta} = q \\ \gamma = \theta - \alpha \end{cases}, \quad (1)$$

where  $V$  is the aircraft longitudinal velocity (m/s),  $q$  is the pitch rate (rad/s),  $\theta$  is the pitch angle (rad),  $\alpha$  is the angle of attack(AOA, rad),  $\gamma$  is the flight path angle(rad),  $z_T$  is the engine pitching arm(m),  $L$  is the lift of the airplane(N),  $D$  is the drag of the airplane(N),  $T$  is the engine thrust(N) and  $M^a$  is the pitching moment of the airplane(N · m). The aerodynamic forces and moment are described as follows.

$$\begin{aligned} L &= \frac{1}{2} \rho V^2 S C_L(\alpha, \delta_e, q, V) \\ D &= \frac{1}{2} \rho V^2 S C_D(\alpha, V) \\ T &= \delta_T \cdot C_T(V) \\ M^a &= \frac{1}{2} \rho V^2 S \bar{c} \cdot C_{M^a}(\alpha, \dot{\alpha}, \delta_e, q) \end{aligned}$$

In the above equations,  $\rho$  is the air mass density(kg/m<sup>3</sup>),  $S$  is the wing area(m<sup>2</sup>),  $\bar{c}$  is the aerodynamic chord(m), and  $C_L$ ,  $C_D$ ,  $C_T$ ,  $C_{M^a}$  are the corresponding aerodynamic coefficients. In order to facilitate the design of the controller, we linearized the equations of motion above using singular perturbations trimmed at  $V=72$  m/s and  $h=400$ m. The linear equations can be noted as:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}. \quad (2)$$

Hence, the state variables are  $\mathbf{x} = [\Delta V \ \Delta \alpha \ q \ \Delta \theta]^T$ , and the inputs are  $\mathbf{u} = [\Delta \delta_e \ \Delta \delta_T]^T$  where  $\Delta V$  is the change of the aircraft velocity (m/s),  $\Delta \alpha$  is the change of the AOA (rad),  $\Delta \theta$  is the change of the pitch angle (rad),  $\Delta \delta_e$  is the change of the elevator angle (rad) and  $\Delta \delta_T$  is the change of the throttle setting.  $\mathbf{A}$  and  $\mathbf{B}$  are corresponding matrices, and can be obtained as follows.

$$\mathbf{A} = \begin{bmatrix} -0.0343 & 3.5405 & 0 & -9.8054 \\ 0.0037 & -0.5052 & 0.9723 & 0 \\ -0.0008 & -0.4966 & -0.3630 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} 5.7889 & 0 \\ -0.0110 & -0.0005 \\ 0.1036 & -0.0069 \\ 0 & 0 \end{bmatrix}$$

The maximum and minimum values of saturations are  $\min \delta_e = -23(\text{deg})$ ,  $\max \delta_e = 17(\text{deg})$ , and  $\min \delta_T = 0$ ,  $\max \delta_T = 1$ .

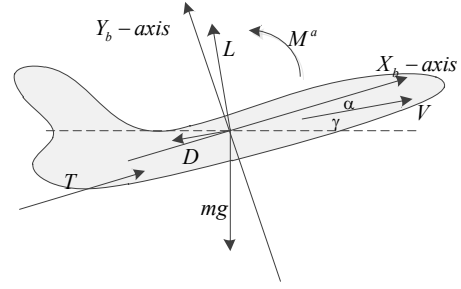


Figure 1. Longitudinal forces and moments analysis scheme

### III. DESIGN OF THE CONTROLLER

In this paper, a pitch angle control loop and a speed control loop were designed separately. Only one control input was presented and the two inputs of the aircraft longitudinal both used the same technique as demonstrated later. The longitudinal attitude control system structure is shown in Fig. 2 below.

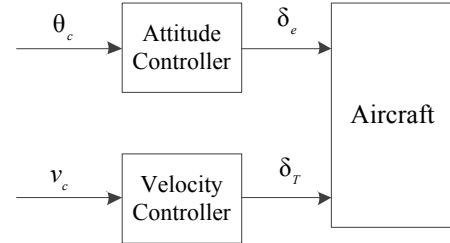


Figure 2. Longitudinal attitude control system

The objective of this paper is to execute a longitudinal attitude controller dealing with some unknown disturbances such as turbulence, gusts, and modeling errors. Since the technology, as a whole, could be viable with the external disturbance and internal uncertainties, the controllers are free to exploit the Active Disturbance Rejection (ADR) controller.

The following figures are a classic ADRC structure and a developed structure.

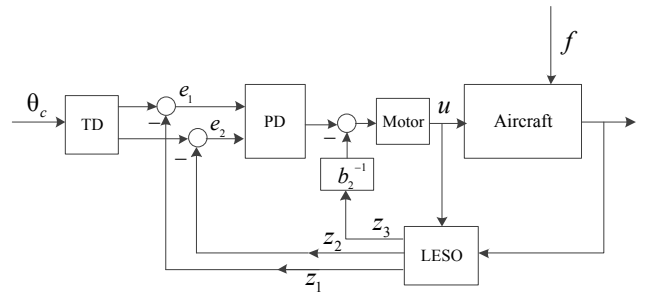


Figure 3. Structure of classic ADRC

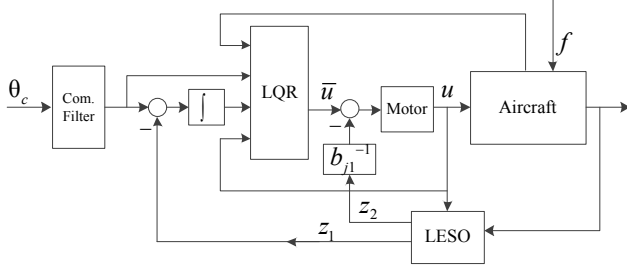


Figure 4. Structure of developed ADRC

The developed ADRC controller is composed of a command filter, an LQR controller and a linear extended state observer. The TD and PD parts have been upgraded. The command filter is used for smoothing the input command for the transition process. It is used to prevent system instability when the input command is suddenly changed and the output cannot be tracked quickly enough. Compared with the traditional tracking differentiator (TD), the command filter is relatively simple to design and has the same function. The LQR controller can improve the dynamic characteristics to the optimum behavior of the control system. It can also easily tune the parameters of the controller.

#### A. Filter design

The filter was designed for filtering high frequency noise in the pilot rod. It also smoothed the transition process. The delay time was set to  $\tau_1 = 0.1$  (second), and its transfer equation is as follows.

$$\frac{\bar{\Theta}_c}{\Theta_c} = \frac{1}{\tau_1 s + 1} \quad (3)$$

#### B. linear ESO design

The extended state observer plays a key role in the ADRC controller. It helps the controller estimate and compensate for disturbance. Its idea is to extend a new variable in the state observer as the total disturbance of the system. For longitudinal aircraft attitude control, we assumed that the entire final disturbance  $f$  was added in the pitch rate of the body axes. We suppose  $q$  to be the  $j$ -th column,  $x_j = q$ . Considering the interference, the system can be expressed as:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} + (0 \cdots e_j \cdots 0)^T f, \quad (4)$$

where  $e_j = 1$ . According to the principles of the ADRC controller design, a linear Extended State Observer (ESO) [11] can be designed as:

$$\dot{z}_1 = z_2 + \mathbf{A}_j \mathbf{x} + \mathbf{B}_j \mathbf{u} - 2\omega_o (z_1 - q) \quad (5)$$

$$\dot{z}_2 = -\omega_o^2 (z_1 - q), \quad (6)$$

where  $\omega_o$  is the observer bandwidth. According to the linear system theory, linear ESO can achieve convergence by choosing  $\omega_o$ , to satisfy  $e = z_1 - q \rightarrow 0$ . On the other hand, linear ESO can also play a filtering role by setting  $\omega_o$  to a proper bandwidth. Note that  $q$  satisfies the equation below

$$\dot{q} = \mathbf{A}_j \mathbf{x} + \mathbf{B}_j \mathbf{u} + f, \quad (7)$$

subtracting (5) from (7), we can get

$$\dot{z}_1 - \dot{q} = z_2 - 2\omega_o (z_1 - q) - f \quad (8)$$

$$f = z_2 - \varepsilon, \quad (9)$$

where  $\varepsilon = 2\omega_o (z_1 - q) + (\dot{z}_1 - \dot{q})$  is the observer error. By taking (9) into (4), the original system can be described as follows.

$$\begin{aligned} \dot{\mathbf{x}} = & \mathbf{Ax} + \mathbf{Bu} + (0 \cdots e_j \cdots 0)^T z_2 \\ & - (0 \cdots e_j \cdots 0)^T \varepsilon \end{aligned} \quad (10)$$

For the above equation, the system receives an estimated value of the disturbance. By contributing the estimate signal  $z_2$ , the compensation can be achieved. Let  $\delta_e$  be the first input, i.e.  $u_1 = \delta_e$ . The control input signal for the system can be designed as:

$$u_1 = \bar{u}_1 - b_{01}^{-1} z_2. \quad (11)$$

Hence,  $b_{01}$  is the estimate of  $b_{j1}$ . By taking (11) into (10), the systems can be expressed as:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{B}\bar{\mathbf{u}} - (0 \cdots e_j \cdots 0)^T \varepsilon. \quad (12)$$

The disturbance for (12) now is converted into the state observer error. By designing the linear ESO, we can limit the error of the observer to a small range, markedly improving the system's disturbance rejection.

#### C. LQR controller design

The LQR controller is designed to achieve an optimal behavior, specifically, a fast response, a small overshoot, and no steady-state error. First, we need to establish the optimal control objective. Control indicators are generally selected as a secondary state which usually consists of the error, the integral of the error, the control input and the derivative of the input, i.e.  $\mathbf{y} = [e_0 \int e_0 \delta_e \dot{\delta}_e]^T$ . The control objective is established as follows.

$$\min J = \int \mathbf{y}^T \mathbf{Q} \mathbf{y} dt \quad (13)$$

Then, an optimal control input needs to be found to satisfy the equation above. The dynamic characteristics of the elevator servo and booster are considered, so the transfer function can be equivalent to

$$G(s) = \frac{1}{\tau_2 s + 1}, \quad (14)$$

where, the delay time is assigned to  $\tau_2 = 1/15$  (second). Establish the following extended systems.

$$\begin{aligned}\dot{\bar{x}} &= \mathbf{F}\bar{x} + \mathbf{G}_1\bar{u}_1 + \mathbf{G}_2\theta_c \\ y &= \mathbf{H}\bar{x} + \mathbf{D}\bar{u}_1\end{aligned}\quad (15)$$

Here, the state variables

are  $\bar{x} = [v \quad \alpha \quad q \quad \theta \quad \bar{\theta}_c \quad \int e_0 \quad \delta_e]^T$ . The coefficient matrices are described below.

$$\mathbf{F} = \begin{bmatrix} & & & & 0 & 0 & \\ & & & & 0 & 0 & \\ & & \mathbf{A} & & 0 & 0 & \mathbf{b}_1 \\ & & & & 0 & 0 & \\ 0 & 0 & 0 & 0 & -\tau_1^{-1} & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\tau_2^{-1} \end{bmatrix}$$

$$\mathbf{G}_1 = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad -\tau_2^{-1}]^T$$

$$\mathbf{G}_2 = [0 \quad 0 \quad 0 \quad 0 \quad -\tau_1^{-1} \quad 0 \quad 0]^T$$

$$\mathbf{H} = \begin{bmatrix} 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\tau_2^{-1} \end{bmatrix}$$

$$\mathbf{D} = [0 \quad 0 \quad 1 \quad \tau_2^{-1}]^T$$

The control law here is  $\bar{u}_1 = -\mathbf{K}\bar{x}$ . By adjusting the weighting matrix  $\mathbf{Q}$ , the gain matrix  $\mathbf{K}$  can be obtained by solving the algebraic Riccati equation. Generally, when a certain diagonal element in  $\mathbf{Q}$  is increased, the corresponding state quantity converges more quickly. In this paper, since the tracking error is focused on the design of objects,  $\mathbf{Q}$  can be tuned by increasing the value of the error integral term. The specific value was set to  $\mathbf{Q} = \text{diag}(0.0001, 1000, 15000, 6)$ . Through this control method, the forward channel modulation parameters can be easily tuned in ADRC technology. The performance of the system can also be improved.

The stability of regular ADRC has been studied in [12]. In this paper, we replaced PD with LQR. Both methods have their own stability theories. By choosing suitable  $\omega_0$ ,  $b_{0l}$ , and  $\mathbf{Q}$  we can get a stable system.

#### IV. SIMULATION RESULTS

The MATLAB/SIMULINK simulation environment under the Windows Operating System was set for the digital simulation of the above algorithm. The B747 longitudinal nonlinear model was applied. On the trimmed point of the aircraft, a five degree pitch angle command was given to validate the dynamic response characteristics. Winds, like gusts and turbulence, were added to the airspeed vector of the aircraft and the uncertainties of the aerodynamic coefficients were added to the model by changing a random percentage of the coefficients directly. The simulation was set to test the

controller's ability of disturbance rejection and also to compare with the linear ADRC [11] and the LQR controller[13].

##### A. Gust

The gust model's mathematical description is below.

$$V_{gust} = \begin{cases} 0 & x < 0 \\ \frac{V_m}{2} \left( 1 - \cos\left(\frac{\pi x}{d_m}\right) \right) & 0 \leq x \leq d_m \\ V_m & x > d_m \end{cases} \quad (16)$$

Hence,  $V_m$  is the gust amplitude,  $d_m$  is the gust length,  $x$  is the distance traveled. Headwind gust was added at the 15th second. Its strength is  $V_m = 13\text{m/s}$ . Results are shown in Fig. 5.

As can be seen from the figure, ADRC can resist the gust but the transition process is not ideal and there is a steady-state error. The LQR controller has a good transition process; however, there is an obvious concussion as the gust influences the system. The ADRC/LQR method has both a preferred process and a steady response as the gust was added to the system. It had inherited the advantages of both methods.

##### B. Turbulence

For the impact of the turbulence, Military Handbook MIL-HDBK-1797 the Dryden model [14] was used. The selected turbulence intensity was  $\sigma = 10^{-5}$  (severe). Five pitch degree of step command was applied to the attitude. The results of the three methods of simulation are shown in Figure 6.

From the figure, LQR and ADRC/LQR the transition process is fast and ideal. During the steady-state, LQR method has larger fluctuations and the fluctuations tend to diverge. While the ADRC/LQR fluctuated in a small range when in stable stage, which proves that ADRC/LQR does have a certain resistance to turbulence.

##### C. Aerodynamic coefficients uncertainties

A 30% uncertainty of the aerodynamic coefficients were considered and gust ( $V_m = 13\text{m/s}$ , headwind) was added to the aircraft. The simulation was run to 100 times. Results are shown in Fig. 7.

From Fig. 7, we can conclude that the transition processes of the step response were nearly the same as the introduction of the uncertainty. The controller suppressed the effects of the system uncertainty. When the gust was included, the maximum deviation of the pitch angle was  $5.25^\circ$ . Its performance, however, was remarkably stable.

#### V. CONCLUSION

A new approach based on the principle of ADRC and LQR was presented for longitudinal landing attitude control. This approach was aimed at solving severe disturbance in large aircraft landing longitudinal attitude control. In this paper, a command filter replaced the tracking differentiator to arrange

the command transient process. The linear ESO was also used. An LQR was applied to achieve an optimal behavior response from the systems. The wind disturbance and aerodynamics coefficients uncertainty were taken into account. Simulation results demonstrated the effectiveness of this approach. It inhibited serious wind interference and adopted the modeling error. In the design of our ADRC/LQR, it is assumed that the disturbance was added on the pitch rate of the body axis. In fact, the wind affects the angle of attack and the airspeed directly. The results proved that our assumptions were applicable.

#### PROBLEMS AND FUTURE WORK

This method was designed by the two controllers separately. The encountered gust, however, caused the speed loop and pitch angle loop to couple slightly. In decoupling, the ADRC Technology may not be optimal, so the next step may include how to optimize the coupling to minimum.

The controller still needs to be optimized for landing quality, and multi-objective parameter optimization must be studied in the future. Future work should also include the application of the method to the aircraft lateral control.

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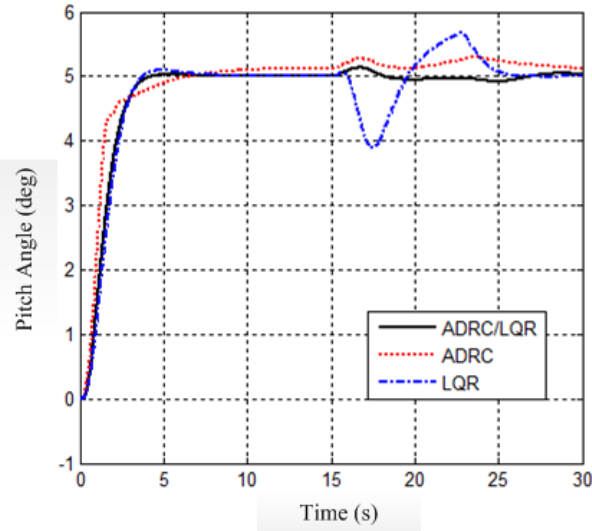


Figure 5. Comparison of Step Responses with Gust.

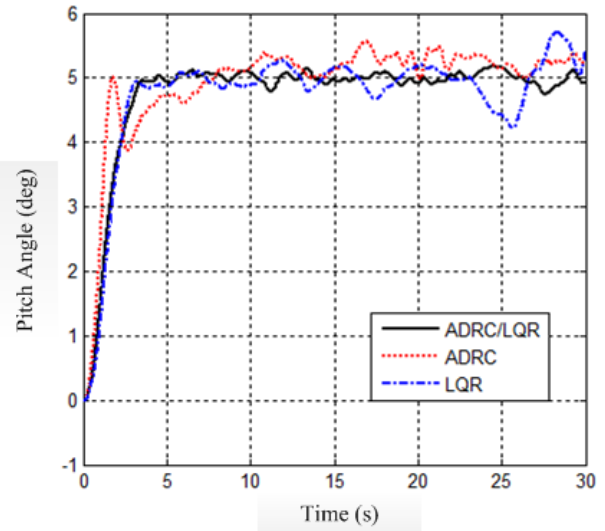


Figure 6. Comparison of Step Responses with Turbulence

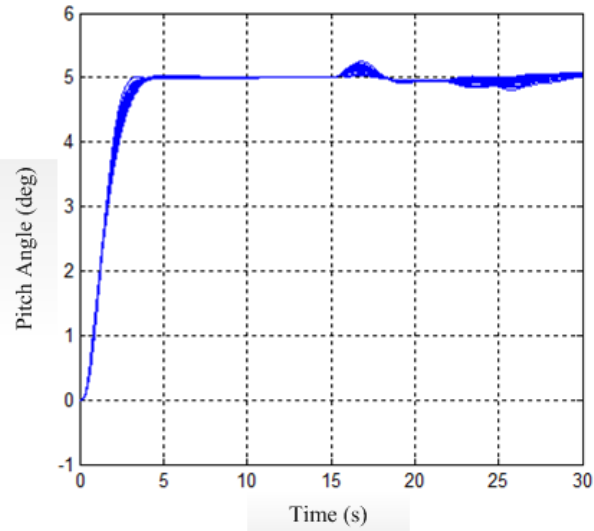


Figure 7. 100 Times Step Responses with Gust and 30% uncertainties of the aerodynamics coefficients