Dedicated Observer-based Approach for Fault Isolation in Wind Turbine System

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Abstract

The problem of fault detection and isolation for a wind turbine benchmark model is addressed in this paper. A dedicated observer based bank of residuals are generated to detect and isolate different sensor faults in the drive train subsystem of a benchmark system model. The faults considered in this paper are rotor and generator speed sensor faults that include fixed value sensor fault in any one of the two redundant speed measurements and a gain factor fault in one of the generator speed measurement. The proposed design detects the above described faults within the required timings specified in the benchmark model and isolation residuals isolate these faults.

Index Terms—wind turbine, dedicated observer scheme (DOS), fault isolation, fault detection.

I. Introduction

A significant part of the world's power production can be attributed to wind turbines [1]–[4]. The size of the standard wind turbine is also increasing with time which inherently demands more reliable and efficient operation of wind power production unit. Turbines in megawatt sizes are expensive and a high reliability is expected to produce maximum power from the given unit. Therefore, advanced fault diagnosis, isolation, and accommodation mechanism needs to be incorporated into the wind turbine to ensure acceptable performance under the occurrence of faults. Mostly, manufactured wind turbines use simplistic schemes to detect and accommodate faults and wind turbine is kept shutdown for maintenance even in case of mild faults.

Fault detection and tolerant control of wind turbine systems has been an attractive field for the researchers in recent years due to increased interest in the wind energy as renewable energy source [2], [3]. Wind turbine modeling and study of sensor and actuator faults based on their severity level is presented in [5] along with model-based diagnosis algorithms. In [6], a benchmark model of wind turbine is proposed for simulation of fault diagnosis and accommodation. An observer based scheme for detection of sensor faults for blade torque sensors is presented in [7]. Dual sensor redundancy is assumed for fault tolerant purpose. Additive and multiplicative faults are considered in this paper. Carl Svard et al. [8] on the other hand used an automated design method for the purpose of fault diagnosis and isolation. An automated design method that minimizes the number of required human decisions and assumptions is proposed. Fault detection in electrical conversion systems are discussed in [9]–[11] and [12]. A reference model based approach is applied for the detection of fault in specified benchmark model in [13] which is robust towards model uncertainties.

Observer based schemes are model based residual generation schemes with the advantage of the structure flexibility which gives more degree of freedom and it may result in reduced order design which is good for on-line implementation. Some examples of observer based schemes used by researchers for fault detection purpose are given next. Unknown input observer scheme for fault detection in coal mills power plant is proposed in [14]. The same scheme applied for estimation of power coefficients for wind turbines is presented in [15]. In [16], wind turbine subsystems i.e pitch system, drive train system and generator converter system are considered for fault detection and isolation. An observer based technique is proposed and for pitch and converter subsystems a Kalman filter based approach is utilized. Residual evaluation is done by applying generalized likelihood ratio test and cumulative variance index. This paper presents a dedicated observer based scheme for fault detection and isolation in benchmark model. Drive train subsystem of wind turbine is considered for the design. Fault types, severity, and time of development study done in [6] suggests the occurrence of sensor faults in pitch angle, rotor, and generator speed measurements for a wind turbine system. In this paper, rotor and generator speed sensor faults are considered for the demonstration and application of the developed technique, however the method can be applied to faults in pitch angle measurements as well. This paper is organized as follows: The wind turbine system description and preliminaries are given in Section II, and in Section III design scheme for fault detection is presented. Simulation results are shown in Section IV and a conclusion is drawn in Section V.

II. System Description And Preliminaries

A. System Description

In this paper, three blade horizontal axis turbine is considered. Wind moves the blades which are connected to the rotor shaft. A gear box is utilized as a link between this shaft and high speed rotor of generator and converter. There are two zones in which wind turbine is controlled, partial power zone and full power zone. In partial power zone, the control objective is to produce maximum possible power for the given wind speed. The ratio of tip speed and wind speed is kept at a certain constant value for this purpose. Converter torque alone is utilized to adjust the rotational speed of the wind turbine rotor in this working zone. In the zone 3, which is full power zone, the converter torque is not changed and blade pitch angle is varied corresponding to current wind speed for controlling the rotational speed. These operational zones are shown in Fig.1.

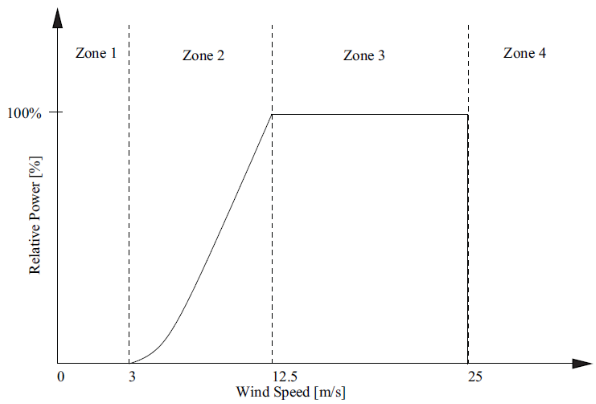

Fig. 1. Illustration of the reference power curve for the wind turbine depending on the wind speed [6].

Zones 2 and 3 are partial and full power zones; respectively. Turbine is kept stand still in zones 1 and 4. Hence only zone 2 and 3 are of importance in our study. The concept of wind turbine operation is illustrated in Fig. 2.

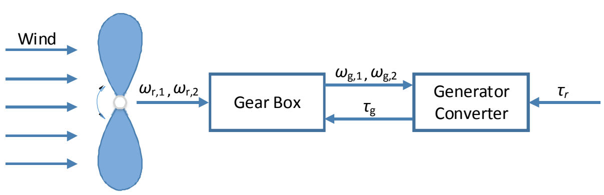

Fig. 2. Illustration of the working principle of the wind turbine drive train.

B. System Model

Drive train system can be modeled as [6].

$$\begin{cases} J_r\dot{\omega}_r(t) = \tau_r(t) - K_{dt}\theta_\triangle(t) - (B_{dt} + B_r)\omega_r(t) \\ \qquad + \dfrac{B_{dt}}{N_g}\omega_g(t) \\ J_g\dot{\omega}_g(t) = \dfrac{\eta_{dt}K_{dt}}{N_g}\theta_\triangle(t) + \dfrac{\eta_{dt}B_{dt}}{N_g}\omega_r(t) \\ \qquad - \left(\dfrac{\eta_{dt}B_{dt}}{N_g^2} + B_g\right)\omega_g(t) - \tau_g(t) \\ \dot{\theta}_\triangle(t) = \omega_r(t) - \dfrac{1}{N_g}\omega_g(t) \end{cases} \tag{1}$$

where J_g represents the moment of inertia of high-speed rotating shaft, J_r is the moment of inertia of the low-speed shaft, K_{dt} is the torsion stiffness of the drive train, B_{dt} is the torsion damping coefficient of the drive train, B_g is the viscous friction of the high-speed shaft, N_g is the gear ratio, η_{dt} is the efficiency of the drive train, and $\theta_\triangle(t)$ is the torsion angle of the drive train. Define state vector as $x_{dt} = [\omega_r\ \omega_g\ \theta_\triangle]^T$, state space model is given as

$$\begin{cases} \dot{x}_{dt} = A_{dt}x_{dt} + B_{dt}\begin{bmatrix}\tau_r \\ \tau_g\end{bmatrix} \\ y_{dt} = C_{dt}x_{dt} \end{cases} \tag{2}$$

where

$$A_{dt} = \begin{bmatrix} -\frac{B_{dt}+B_r}{J_r} & \frac{B_{dt}}{N_gJ_r} & -\frac{K_{dt}}{J_r} \\ \frac{\eta_{dt}B_{dt}}{N_gJ_g} & -\frac{\eta_{dt}B_{dt}}{N_g^2J_g} - \frac{B_g}{J_g} & \frac{\eta_{dt}K_{dt}}{N_gJ_g} \\ 1 & -\frac{1}{N_g} & 0 \end{bmatrix}$$

$$B_{dt} = \begin{bmatrix} \frac{1}{J_r} & 0 \\ 0 & -\frac{1}{J_g} \\ 0 & 0 \end{bmatrix}, \quad C_{dt} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

y_{dt} measures rotor and generator speeds ω_r and ω_g respectively. The input to the drive train is the aerodynamic torque τ_r, provided by the wind gusts and the generator torque τ_g, controlled by the converter which is provided with the torque reference τ_{ref}. The aerodynamic torque is estimated as [6]

$$\tau_r(t) = \frac{1}{2\omega_r(t)}\rho A v_r^3(t) C_p(\lambda(t), \beta(t)) \qquad [Nm] \tag{3}$$

Where ρ is the density of the air, A is the area spanned by the turbine blades while rotating, $\beta(t)$ represents the pitch angle of the turbine rotor blades, $\lambda(t)$ is the tip speed ratio of the blade. Equation (3) estimates τ_{aero} based on an assumed $v_r(t)$, measured $\beta(t)$ and $\omega_r(t)$.

III. Design Scheme

A. Basic Idea

This approach utilizes the idea of design of dedicated observers scheme applied for fault detection and isolation [17]. Instead of fault distribution matrices E_f, F_f, we use the modified matrices E_f^i, F_f^i, E_d^i and F_d^i where $i = 1, \cdots, k_f$, as explained in subsection B. Then, we design a bank of residual generators $r^i(p)$, each residual is sensitive to i_{th} fault only. Hence, fault isolation is achieved.

B. Residual Generator Design

Fig. 3 shows a schematic of a dedicated observer scheme (DOS) for fault detection and isolation.

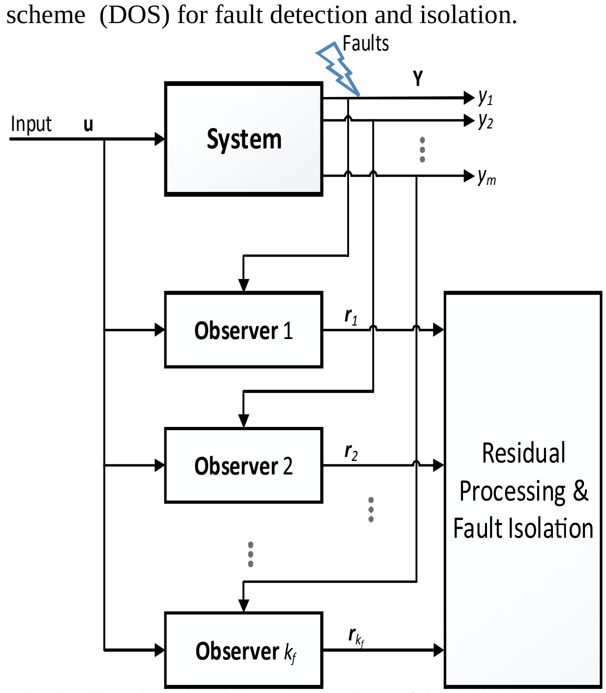

Fig. 3. Illustration of dedicated observer scheme (DOS) for fault detection and isolation. $k_f \leq m$

In the following, we derive an approach to the design of residual generator for fault isolation purpose. Consider a system model

$$\begin{cases} \dot{x} = Ax + Bu + E_f f \\ y = Cx + Du + F_f f \end{cases} \quad (4)$$

with (A, B, C, D) and (A, E_f, C, F_f) as minimal state space realization. A simple diagnostic observer would be

$$\begin{cases} \dot{\eta}(t) = G\eta(t) + Hu(t) + Ly(t) \\ r(t) = vy(t) - w\Phi(t) - vDu(t) \end{cases} \quad (5)$$

with G, H, L, v and w satisfying the Luenberger conditions [17].

1) G is stable.
2) $TA - GT = LC$, $H = TB - LD$
3) $vC - wT = 0$, $q = vD$

where

$$G = \begin{bmatrix} G_o & g \end{bmatrix}, \; G_o = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 1 & 0 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 1 & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \in R^{s\times(s-1)}$$

$$g = \begin{bmatrix} g_1 \\ \vdots \\ g_s \end{bmatrix}, \; H_{fs} = \begin{bmatrix} F_f & 0 & \cdots & 0 \\ CE_f & F_f & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ CA^{s-1}E_f & \cdots & CE_f & F_f \end{bmatrix}$$

$$w = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}^T, \; v_s = \begin{bmatrix} v_{s,0} & \cdots & v_{s,s} \end{bmatrix}$$

$$T = \begin{bmatrix} v_{s,1} & v_{s,1} & \cdots & v_{s,s-1} & v_{s,s} \\ v_{s,2} & \cdots & \cdots & v_{s,s} & 0 \\ \vdots & \cdots & \cdots & \vdots & \vdots \\ v_{s,s} & 0 & \cdots & \cdots & 0 \end{bmatrix} \begin{bmatrix} C \\ CA \\ \vdots \\ \vdots \\ CA^{s-2} \\ CA^{s-1} \end{bmatrix}$$

$$v_s \begin{bmatrix} C \\ CA \\ \vdots \\ CA^s \end{bmatrix} = 0, \; v = v_{s,s}, \; q = vD$$

$$L = -\begin{bmatrix} v_{s,0} \\ v_{s,1} \\ \vdots \\ v_{s,s-1} \end{bmatrix} - gv_{s,s}$$

Now, to apply the same method for fault isolation we need to introduce the following notations,
for $i = 1, \cdots, k_f$

$$E_f^i = \begin{bmatrix} e_{f1} & \cdots & e_{fi-1} & e_{fi+1} & \cdots & e_{fk_f} \end{bmatrix},$$
$$F_f^i = \begin{bmatrix} f_{f1} & \cdots & f_{fi-1} & f_{fi+1} & \cdots & f_{fk_f} \end{bmatrix}$$

The matrices E_f^i and F_f^i consist of all columns of E_f and F_f respectively, except the i_{th} one to be multiplied with the fault which needs to be detected and isolated from other faults. Define

$$H_{d,s}^i = \begin{bmatrix} F_f^i & O & \cdots & O \\ CE_f^i & F_f^i & \ddots & \vdots \\ \vdots & \ddots & \ddots & O \\ CA^{s-1}E_f^i & \cdots & CE_f^i & F_f^i \end{bmatrix}, \quad i = 1, \cdots, k_f$$

$$H_{f,s}^i = \begin{bmatrix} f_{fi} & 0 & \cdots & 0 \\ Ce_{fi} & f_{fi} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ CA^{s-1}e_{fi} & \cdots & Ce_{fi} & f_{fi} \end{bmatrix}, \quad i = 1, \cdots, k_f$$

We need to find k_f parity vectors, $v_{s_i}^i \;\; i = 1, \cdots, k_f$, such that

$$v_{s_i}^i H_{d,s}^i = 0, \quad i = 1, \cdots, k_f$$

Corresponding to each parity vector, a residual will be generated. The bank of residual generators can be written from (5) as

$$\begin{cases} \dot{\eta}^i(t) = G^i\eta(t) + H^i u(t) + L^i y(t) \\ r^i(t) = v^i y(t) - w^i\Phi(t) - v^i Du(t) \end{cases} \quad (6)$$

Note that $r^i(p)$ will only depend on $f_i(p)$. The existence condition for the perfect fault isolation is

$$rank[H_{f,s}^i \; H_{os} \; H_{d,s}^i] > rank[H_{os} \; H_{d,s}^i]$$

we have to find v_s^i such that

$$v_s^i[H_{os} \; H_{d,s}^i] = 0, \qquad v_s^i H_{f,s}^i \neq 0 \quad (7)$$

C. Algorithm for the design of DOS for fault isolation

Following is the procedure for designing a diagnostic observer for generating bank of residuals to isolate faults as presented in [17].

1) Step 1 Partition the fault distribution matrices E_F, F_f, find $H_{f,s}^i$ and solve

$$v_{s_i}^i[H_{f,s}^i \; H_{d,s}^i] = [\triangle \; 0] \;\; i = 1, \cdots, k_f, \; \triangle \neq 0$$

for $v_{s_i}^i$.

2) Step 2 Construct the residual generator as shown in (6), where

$$G_i = \begin{bmatrix} G_o & g^i \end{bmatrix}, \; G_o = \begin{bmatrix} 0 & 0 & \cdots & 0 \\ 1 & 0 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 1 & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix}, \; g^i = \begin{bmatrix} g_1^i \\ \vdots \\ g_s^i \end{bmatrix}$$

$$H^i = \begin{bmatrix} v_{s,1}^i & v_{s,1}^i & \cdots & v_{s,s-1}^i & v_{s,s}^i \\ v_{s,2}^i & \cdots & \cdots & v_{s,s}^i & 0 \\ \vdots & \ddots & \ddots & \vdots & \vdots \\ v_{s,s}^i & 0 & \cdots & \cdots & 0 \end{bmatrix} \begin{bmatrix} CB \\ CAB \\ \vdots \\ \vdots \\ CA^{s-2}B \\ CA^{s-1}B \end{bmatrix}$$

$$L^i = -\begin{bmatrix} v_{s,0}^i \\ v_{s,1}^i \\ \vdots \\ v_{s,s-1}^i \end{bmatrix} - g^i v_{s_i,s_i}^i, \; w^i = [0 \; \cdots \; 0 \; 1]$$

IV. Simulation Results

For the benchmark model in [6], a number of faults for different parts of wind turbine are given. These faults re inspired from the real faults that appear in the wind turbine. This paper deals with a subset of these faults from the benchmark model. In this paper, only faults 4 and 5 are considered which are the faults in the drive train subsystem. These faults are defined in [6] as, fault 4 is a fixed value fault on rotor speed measurement equal to 1.4 rad/s for the time from 1500 to 1600 s. Fault number 5 is a gain factor of 0.9 on generator speed measurement no. 2 active from 1000 to 1100 seconds.

A graphical overview of the benchmark model is shown in Fig. 4. The input wind speed sequence used in this benchmark model is shown in Fig. 5. Fault 4 affects the rotor speed measurements coming from sensor 1. This faulty reading is shown in Fig. 6 and fault remains active from 1500 second to 1600 second. Fault number 5 affects the generator speed measurements coming from sensor 2. This faulty reading is shown in Fig. 7. This gain factor fault remains active from 1000 second to 1100 second. Figures 8 and 9 show the outputs of the fault isolation residual generators after residual processing. The faults are detected within the time limits imposed in [6]. Fault isolation residual 1 shown in Fig. 8 is only sensitive to the rotor speed measurement sensor fault and the residual is significantly high from 1500-1600 seconds. This isolation residual is insensitive to the fault present from 1000 to 1100 seconds. Note that in the simulation run, both faults were present at their prescribed timings. Similarly, Fig. 9 shows a fault isolation residual 2 which is insensitive to the fault number 4. Hence each residual is sensitive only to the fault for which it is designed so fault isolation is achieved.

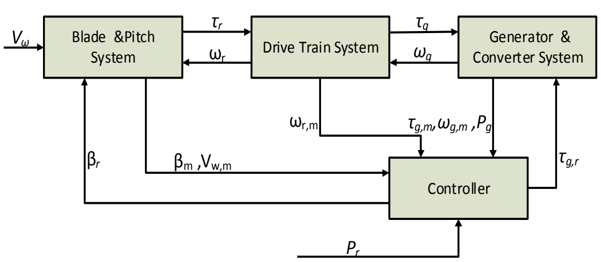

Fig. 4. Overview of the benchmark model. It consists of four parts: blade and pitch systems, drive train system, generator and converter system, and controller.

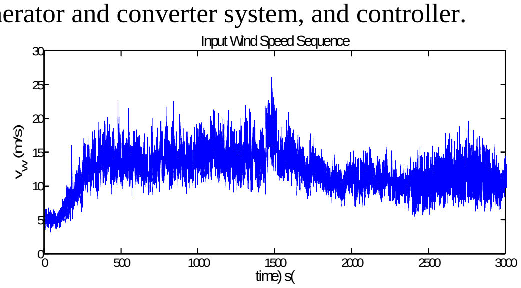

Fig. 5. Wind speed sequence used in the benchmark model. This wind speed covers the range 520 m/s, which is a good coverage range of normal operational (zone2 and zone3 from Fig.1) of a wind turbine.

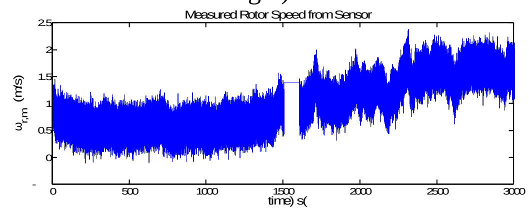

Fig. 6. Rotor speed measurement from Sensor 1 as output of the simulation. It can be seen that this sensor signal is corrupted with a fixed value for the time interval 1500 to 1600s.

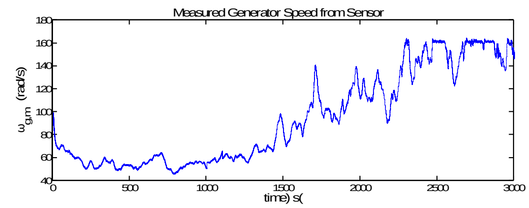

Fig. 7. Generator speed measurement from Sensor 2 as output of the simulation. This sensor reading has a gain factor fault of 0.9 in the time period 1000 to 1100s.

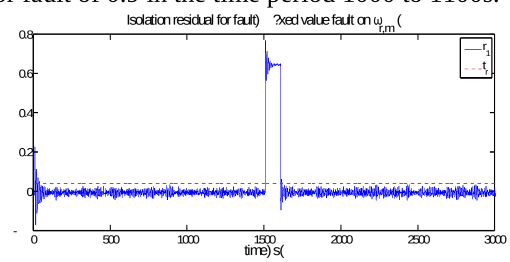

Fig. 8. Isolation residual for fault 4. Fault is detected within prescribed time and residual is clearly insensitive to fault 5, hence isolation is achieved.

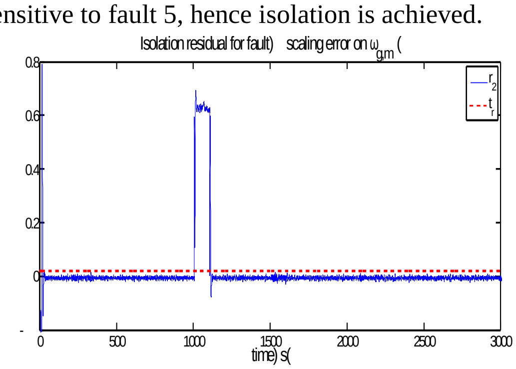

Fig. 9. Isolation residual for fault 5. Residual remains around zero position for 1500 to 1600 seconds, hence it is only sensitive to fault 5.

V. Conclusion

In this paper, a dedicated observer based scheme is developed to generate bank of residuals. These residuals are processed to diagnose and isolate sensor fault scenarios in a drive train subsystem of specified benchmark model presented in [6]. By utilizing certain structure of system model, the fault isolation residuals are designed. Future research work will include the integration of diagnosis, isolation, and faulttolerant control design for the wind turbine system.

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Quotations

- About the only person we ever heard of that wasn't spoiled being lionized was a Jew named Daniel.
  G. D. PRENTICE
- Old houses mended, Cost little less than new before they're ended.
  Colley Cibber
- Architecture is frozen music.
  Goethe
- Ah, to build, to build! That is the noblest of all the arts.
  Longfellow, Michelangelo
- Arguments out of a petty mouth are unanswerable.
  Addison
- Many can argue; not many converse.
  Alcoit
- Wise men argue causes, and fools decide them.
  Anacharsis
- When Bishop Berkeley said, "there was no matter," proved it-'twas no matter what he said.
  Byron, Don Juan
- Neither irony nor sarcasm is argument.
  Rufus Choate
- I am bound to furnish my antagonists with arguments, but not with comprehension.
  Disraeli
- How agree the kettle and the earthen pot together?
  Ecclesiastes. XIII2
- Strong and bitter words indicate a weak cause.
  Vlcror Hugu
- Insolence is not logic; epithets are the arguments of malice.
  Ingersoll
- Myself when young did eagerly frequent

Doctor and Saint, and heard great argument
About it and about: but evermore
Came out by the same door where in I went.
Omar Khayyam
Rubaiyat

- Never argue at the dinner table, for the one who is not hungry always gets the best of the argument.
  Whately
- When people agree with me I always feel that I must be wrong.
  Wilde, The Critic as an Artist
- Art, as far as it is able, follows nature, as a pupil imitates his master; thus your art must be, as it were, God's grandchild.
  Damte, Inferno
  - Great art is as irrational as great music. It is mad with its own loveliness.
    George Jean Nathan, House of Soton

A picture is a poem without words.
Horace

Art hath an enemy called ignorance.
Ben Jonson