Observer-based FDI for Gain Fault Detection in Ship Propulsion Benchmark

a Geometric Approach

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OBSERVER-BASED FDI FOR GAIN FAULT DETECTION IN SHIP PROPULSION BENCHMARK - A GEOMETRIC APPROACH [1]

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Abstract: A geometric approach for input-affine nonlinear systems is briefly described and then applied to a ship propulsion benchmark. The obtained results are used to design a diagnostic nonlinear observer for successful FDI of the diesel engine gain fault.

Keywords: input-affine nonlinear systems, fault detection, fault isolation, nonlinear observer, geometric approach.

1. INTRODUCTION

Interest in fault detection and isolation (FDI) for nonlinear systems has grown significantly in recent years. The design of FDI is motivated by the need for knowledge about occurring faults in fault-tolerant control systems (FTCS); (Patton, 1997). The idea of FTCS systems is to detect, isolate, and accommodate occurring faults in such a way that the systems can still perform in a required manner. One prefers reduced performance after occurrence of a fault to the shut down of subsystems; (Blanke, 1999). Hence, the idea of fault-tolerance can be applied to ordinary industrial processes that are not categorized as high risk applications, but where high availability is desirable, e.g. a ship propulsion system. In the past mainly linear FDI methods were developed, but as most plants show nonlinear behavior, nonlinear methods are preferred (Frank *et al.*, 1999).

Among different approaches for FDI the geometric methods are of high interest. The geometric theory offers various advantages as it gives a general formulation of the FDI problem, and is more compact and more transparent for more general systems (like the nonlinear systems) than the algebraic approach. In recent years the existing geometric theory for the residual generation in linear systems based on the original work by Massoumnia (Massoumnia *et al.*, 1989; Massoumnia, 1986) has been extended. Formulations for different classes of nonlinear systems were derived in order to handle state-affine nonlinear systems (Hammouri *et al.*, 1998) and lately also the class of input-affine systems (DePersis and Isidori, 2000*a*; Hammouri *et al.*, 1999). (DePersis and Isidori, 2000*a*) presents a detailed geometric description of how to tackle the residual generation problem for nonlinear systems.

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The geometric approach towards FDI for input-affine nonlinear systems has gained high interest in the last two years. However, until now, only little experience with its application has been obtained.

In this paper the geometric approach is briefly described and then applied to a ship propulsion benchmark. As a result a locally observable subsystem is obtained. The subsystem is only affected by the gain fault when the pitch measurement is considered to be fault-free. Correspondingly, a diagnostic nonlinear observer is designed to detect and isolate the engine gain fault. Simulation results obtained by applying the residual generator to the simulation model of the ship propulsion system are presented. Finally, the residual performance is discussed in detail.

2. GEOMETRIC APPROACH TO NONLINEAR FDI

In the following the geometric approach to nonlinear FDI by (DePersis, 1999; DePersis and Isidori, 2000*a*) is briefly reviewed for systems of the form:

$$\begin{aligned}\dot{x} &= f(x) + \sum_{i=1}^{m} g_i(x)u_i + \sum_{i=1}^{s} p_i(x)w_i + l(x)\nu \\ y_j &= h_j(x), \quad j \in \mathbf{l}\end{aligned} \tag{1}$$

where the states x are defined on a neighborhood $\mathcal{N}$ of the origin in $\mathbb{R}^n$. u_i, $i \in \mathbf{m} = \{1, \ldots, m\}$, denotes the inputs and y_j, $j \in \mathbf{l}$, the outputs of the system. $\nu \in \mathbb{R}$ is a scalar fault signal with the nonlinear fault signature $l(x)$. $f(x)$, $g_i(x), i \in \mathbf{m}$, $l(x)$, and $p_i(x), i \in \mathbf{s}$ are smooth vector fields and $h_j(x), j \in \mathbf{l}$ are smooth functions. Furthermore, let $f(0) = 0$ and $h(0) = 0$. The disturbances and fault signals from which the fault ν has to be isolated are denoted by $w = [w_1\, w_2 \ldots w_s]^T \in \mathbb{R}^s$.

In order to detect the fault ν and isolate it from the disturbances and other faults (w_i) in System (1) the following problem is formulated as described in (DePersis, 1999):

Definition 1. Considering a system of the form (1) the local nonlinear fundamental problem of residual generation (l-NLFPRG) is to find, if possible, a filter:

$$\begin{aligned}\dot{z} &= \tilde{f}(y, z) + \sum_{i=1}^{m} \tilde{g}_i(y, z)u_i \\ r &= \tilde{h}(y, z)\end{aligned} \tag{2}$$

where $z \in \mathbb{R}^q$, $r \in \mathbb{R}^p$, $1 \le p \le l$. $\tilde{f}(y, z)$, $\tilde{g}_i(y, z), i \in \mathbf{m}$, and $\tilde{h}(y, z)$ are smooth vector fields, with $\tilde{f}(0, 0) = 0$ and $\tilde{h}(0, 0) = 0$, such that on a neighborhood $\mathcal{N}^e$ of $x^e = (x, z) = (0, 0)$, where x_e describes of the cascaded system formed by (1) and (2), the following properties hold:

- (i) *if $\nu = 0$, then r is unaffected by u_i, w_j, $\forall i, j$;*
- (ii) *r is affected by ν;*
- (iii) $\lim_{t\to\infty} \|r(t; x^0, z^0; u, \nu = 0, w)\| = 0$ *for any initial condition x^0, z^0 in a suitable set containing the origin $(x, z) = (0, 0)$.*

For linear systems Definition 1 reduces exactly to the linear Fundamental problem of residual generation (FPRG) defined in ((Massoumnia *et al.*, 1989)). Both describe the problem of detecting a fault and isolating it from disturbances and other faults. Condition (i) in Definition 1 assures that the control signals u and the disturbances (and other faults) w do not affect (i.e. do not become visible in) the residual r in the fault-free case ($\nu = 0$). If fault ν occurs Condition (ii) assures that the fault affects the residual. Condition (iii) considers the stability of Filter (2). Note that the convergence to zero of the residual is required in absence of the fault ($\nu = 0$).

A solution for the l-NLFPRG can be obtained by the help of the results presented in (DePersis and Isidori, 2000*b*). It is based on the calculation of the largest observability codistribution (o.c.a.$((\Sigma_*^P)^\perp)$) contained in $P^\perp$ the annihilator of P (i.e. $P^\perp = \{x^{'}; x^{'}x = 0, \forall x \in P\}$), where P is the distribution spanned by the disturbance vectors $p_i, i \in \mathbf{s}$: $P = span\{p_1, \ldots, p_s\}$. For System (1) one can calculate o.c.a.$((\Sigma_*^P)^\perp)$ by the following two algorithms (details are given in (DePersis and Isidori, 2000*b*)):

Computing Σ_*^P:

$$\begin{aligned}S_0 &= \overline{P} \\ S_{k+1} &= \overline{S}_k + \sum_{i=0}^{m} [g_i, \overline{S}_k \cap Ker\{dh\}]\end{aligned} \tag{3}$$

where $\overline{\Delta}$ denotes the involutive closure of a distribution Δ. For every constant distribution Δ it holds that $\overline{\Delta} = \Delta$. The notation $[\xi, \zeta]$ with $\xi, \zeta \in \mathbb{R}^n$ denotes the *Lie bracket*. $g_0 \ldots g_m$ stand for the column vectors of $g(x)$ **and** for $f(x)$, which is written as $f(x) = g_0(x)$ to ease the notation. $Ker\{dh\}$ denotes the distribution annihilating the differentials of the rows of the mapping $h(x)$. If there exists a k^* such that:

$$S_{k^*+1} = \overline{S}_{k^*}$$

then set $\Sigma_*^P = \overline{S}_{k^*}$ and continue with the following algorithm.

Computing o.c.a.$((\Sigma_*^P)^\perp)$:

$$\begin{aligned}Q_0 &= (\Sigma_*^P)^\perp \cap span\{dh\} \\ Q_{k+1} &= (\Sigma_*^P)^\perp \cap \left(\sum_{i=0}^{m} L_{g_i} Q_k + span\{dh\} \right)\end{aligned} \tag{4}$$

where $span\{dh\}$ is the codistribution spanned by the differentials of the rows of the mapping $h(x)$ and L denotes the *Lie derivative*. Suppose that all codistributions Q_k of this sequence are nonsingular, so that there is an integer $k^* \leq n-1$ such that $Q_k = Q_{k^*}$ for all $k > k^*$, then

$$\text{o.c.a.}((\Sigma_*^P)^\perp) = Q_{k^*}.$$

When the distribution Σ_*^P is well-defined and nonsingular, and $\Sigma_*^P \cap Ker\{dh\}$ is a smooth distribution, then o.c.a.$((\Sigma_*^P)^\perp)$ is the maximal (in the sense of codistribution inclusion) observability codistribution which is locally spanned by exact differentials and contained in $P^\perp$. The corresponding unobservability distribution Q can be obtained by:

$$Q = (\text{o.c.a.}((\Sigma_*^P)^\perp))^\perp$$

For more details about the o.c.a. algorithm and the calculation of Q the reader is referred to (DePersis and Isidori, 2000*a*).

As a result of the algorithms Q is the smallest involutive unobservability distribution that contains P (the disturbance effects) due to the maximality of o.c.a.$((\Sigma_*^P)^\perp)$.

(DePersis and Isidori, 2000*b*) show that if

$$span\{l(x)\} \not\subseteq (\text{o.c.a.}((\Sigma_*^P)^\perp))^\perp = Q$$

it is possible under certain conditions to find a change of state coordinates $\tilde{x} = \Phi(x)$ and a change of output coordinates $\tilde{y} = \Psi(y)$, defined locally around $x = 0$ and, respectively, $y = 0$, such that, in the new coordinates, the system (1) admits the following normal form (Proposition 3 in (DePersis and Isidori, 2000*b*)):

$$\begin{aligned}
\dot{\tilde{x}}_1 &= \tilde{f}_1(\tilde{x}_1, \tilde{x}_2) + \tilde{g}_1(\tilde{x}_1, \tilde{x}_2)u + \tilde{l}_1(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)\nu \\
\dot{\tilde{x}}_2 &= \tilde{f}_2(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3) + \tilde{g}_2(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)u \\
&\qquad + \tilde{p}_2(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)w + \tilde{l}_2(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)\nu \\
\dot{\tilde{x}}_3 &= \tilde{f}_3(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3) + \tilde{g}_3(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)u \\
&\qquad + \tilde{p}_3(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)w + \tilde{l}_2(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3)\nu \\
\tilde{y}_1 &= h_1(\tilde{x}_1) \\
\tilde{y}_2 &= \tilde{x}_2
\end{aligned}$$

where the states $\tilde{x}_2$ are all measured. Output $\tilde{y}_1$ is affected by the states $\tilde{x}_1$, but not by the other states $\tilde{x}_2$ and $\tilde{x}_3$. Hence, the following subsystem can be subtracted:

$$\begin{aligned}
\dot{\tilde{x}}_1 &= \tilde{f}_1(\tilde{x}_1, \tilde{y}_2) + \tilde{g}_1(\tilde{x}_1, \tilde{y}_2)u + \tilde{l}_1(\tilde{x}_1, \tilde{y}_2, \tilde{x}_3)\nu \\
\tilde{y}_1 &= h_1(\tilde{x}_1)
\end{aligned} \tag{5}$$

which, obviously, when it admits an observer can be used to solve the corresponding l-NLFPRG. The estimation error $e = \tilde{y}_1 - \hat{\tilde{y}}_1$ is only affected by the unknown fault signal ν. Hence, it can by construction be used as residual r that fulfills all conditions given in Definition 1 as long as $\tilde{l}_1(\tilde{x}_1, \tilde{x}_2, \tilde{x}_3) \neq 0$.

3. SHIP PROPULSION BENCHMARK

The complete mathematical model for the benchmark is described in (Izadi-Zamanabadi and Blanke, 1998). The subsystems of interest in this paper include dynamics for ship speed, propeller, and the prime mover. The essence is a model where developed thrust and torque are function of diesel throttle position Y, pitch angle θ, shaft speed n and ship speed U. The corresponding measured variables are Y_m, θ_m, n_m and U_m.

Diesel engine and shaft dynamic equations are:

$$Q_{\text{eng}} = k_y Y \tag{6}$$

$$I_m \dot{n} = Q_{\text{eng}} - Q_{\text{prop}}, \tag{7}$$

where Q_{eng} is the engine's generated torque, k_y is gain constant, I_m the shaft inertia, and Q_{prop} denotes the propellers developed torque.

Developed propeller thrust T_{prop} and torque Q_{prop} are given by the following (approximate) quadratic relations (for forward movement)

$$T_{\text{prop}} = T_{nn}\theta n^2 + T_{nU} n U \tag{8}$$

$$Q_{\text{prop}} = Q_{nn}\theta n^2 + Q_{nU}\theta n U \tag{9}$$

The coefficients T_{nn}, T_{nU}, Q_{nn} and Q_{nU} are in fact complex functions of pitch angle θ (see (Izadi-Zamanabadi and Blanke, 1998) for details). They are calculated from tables of data which are obtained from sea trial.

Ship speed dynamics with corresponding hull resistance is described by the first order equation

$$m\dot{U} = R(U) + (1 - t_T)T_{\text{prop}} \tag{10}$$

Ship's resistance to motion $R(U)$ through the water can be described by a resistance curve, which is a third to fifth order polynomial in U. m is the the ship weight and t_T is the thrust deduction number (is a known value).

Fault scenarios: In the described subsystem two faults are considered (in compliance with the original FDI scenario of the benchmark (Izadi-Zamanabadi and Blanke, 1998)). These are the diesel engine gain fault Δk_y and the shaft speed measurement fault Δn_{sensor}. The pitch measurement θ_m is assumed to be non-faulty in this case.

4. RESULTS OBTAINED BY THE GEOMETRIC APPROACH

The geometric method for FDI in Section 2 is applied to the ship propulsion system described in the previous section. In order to obtain a system as given by (1) the considered subsystem of the benchmark can be stated as follows:

$$
\begin{aligned}
\dot{x} &= f(x) + g(x)u + p(x)w + l(x)\nu \\
y_1 &= n_m = n + x_{\Delta n} \\
y_2 &= U_m = U
\end{aligned} \tag{11}
$$

where

$$
x = \begin{pmatrix} n & U & x_{\Delta n} \end{pmatrix}^T, \; u_1 = Y, \quad u_2 = \theta_m
$$

$$
\nu = \Delta k_y Y \qquad , \; w = \dot{\Delta n}_{sensor}
$$

and

$$
f(x) = \begin{pmatrix} 0 \\ \frac{1}{m}R(U) + \frac{1-t_T}{m} T_{|n|U} nU \\ 0 \end{pmatrix},
$$

$$
g_1(x) = \begin{pmatrix} \frac{1}{I_m} k_y \\ 0 \\ 0 \end{pmatrix}
$$

$$
g_2(x) = \begin{pmatrix} -\frac{1}{I_m}\left[Q_{|n|n} n^2 + Q_{|n|U} nU\right] \\ \frac{1-t_T}{m} T_{|n|n} n^2 \\ 0 \end{pmatrix}
$$

$$
p(x) = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \text{and} \quad l(x) = \begin{pmatrix} \frac{1}{I_m} \\ 0 \\ 0 \end{pmatrix}
$$

In (11) the shaft speed sensor fault is implemented as a pseudo-actuator fault $\dot{\Delta n}_{sensor}$ in order to obtain the form (1). This is done following a procedure described in (Hashtrudi-Zad and Massoumnia, 1999) by adding the following additional linear dynamics to the original system:

$$
\begin{aligned}
\dot{x}_{\Delta n} &= A_{\Delta n} x_{\Delta n} + L_{\Delta n} \nu_{\Delta n} \\
y_{\Delta n} &= C_{\Delta n} x_{\Delta n} = \Delta n_{sensor}
\end{aligned}
$$

where $\nu_{\Delta n} = \dot{\Delta n}_{sensor} = w$, $A_{\Delta n} = 0$, and $L_{\Delta n} = C_{\Delta n} = 1$.

The diesel engine gain fault is in its nature a multiplicative fault affecting the system parameter k_y. In (11) it is modeled as an additive fault by considering $\nu = \Delta k_y Y$. Its magnitude depends on the diesel throttle position Y. This is natural as the gain fault's impact becomes bigger the higher the diesel intake to the engine. If $Y = 0$ the diesel engine is not running, hence, the fault would not affect the system's operation anyway.

The goal is now to solve the l-NLFPRG for system (11), i.e. to detect the diesel engine gain fault $\nu = \Delta k_y Y$ and isolate it from the shaft speed measurement fault Δn_{sensor}. Hence, the latter is considered as disturbance w. The algorithms (3) and (4) are initiated with:

$$
P = span\{p_1\} = span\{\begin{pmatrix} 0 & 0 & 1 \end{pmatrix}^T\}
$$

and lead to the following result (detailed calculations can be found in (Lootsma, 2001)):

$$
Q = (\text{o.c.a.}((\Sigma_*^P)^\perp))^\perp = P = span\{\begin{pmatrix} 0 & 0 & 1 \end{pmatrix}^T\}
$$

hence

$$
span\{l(x)\} \not\subseteq Q \quad \text{and} \quad span\{p(x)\} \subseteq Q
$$

Following Proposition 3 in (DePersis and Isidori, 2000*b*) one can then obtain the following subsystem, which corresponds to (5) and obviously is not affected by the shaft speed sensor fault:

$$
\begin{aligned}
\dot{n} = \frac{1}{I_m}(k_y Y + \nu) - \frac{1}{I_m} Q_{|n|U}\, n\, U\, \theta_m \\
- \frac{1}{I_m} Q_{|n|n}\, n^2\, \theta_m
\end{aligned} \tag{12}
$$

$$
\begin{aligned}
\dot{U} &= \frac{1}{m}R(U) + \frac{1-t_T}{m}\left[T_{|n|U}\, n\, U + T_{|n|n}\, n^2\, \theta_m\right] \\
y &= U
\end{aligned} \tag{13}
$$

5. DIAGNOSTIC OBSERVER DESIGN

Subsystem (12) and (13) is a good starting point to obtain successful FDI that enables detection of the diesel engine gain fault and isolation from the shaft speed sensor fault. Hence, the following diagnostic observer is proposed to achieve FDI:

$$
\begin{aligned}
\dot{\hat{n}} = \frac{1}{I_m} k_y Y_m - \frac{1}{I_m} Q_{|n|U}\, \hat{n}\, \hat{U}\, \theta_m \\
- \frac{1}{I_m} Q_{|n|n}\, \hat{n}^2\, \theta_m + K_{\Delta k_y}^{\hat{n}}(U_m - \hat{U})
\end{aligned} \tag{14}
$$

$$
\begin{aligned}
\dot{\hat{U}} &= \frac{1}{m}R(\hat{U}) + \frac{1-t_T}{m}\left[T_{|n|U}\, \hat{n}\, \hat{U} + T_{|n|n}\, \hat{n}^2 \theta_m\right] \\
&\qquad + K_{\Delta k_y}^{\hat{U}}(U_m - \hat{U})
\end{aligned} \tag{15}
$$

$$
\hat{y} = \hat{U}
$$

with the diesel throttle position Y and the pitch measurement θ_m as external inputs. The observer structure corresponds to a form like:

$$
\begin{aligned}
\dot{\hat{x}} &= \hat{f}(\hat{x}) + \hat{g}(\hat{x})u + K(y - \hat{y}) \\
\hat{y} &= h(\hat{x})
\end{aligned}
$$

The function $\hat{f}(x) + \hat{g}(x)u$ is globally Lipschitz for the complete operating range:
$\Omega_x = \{x | 0 < n < n_{max}; 0 < U < U_{max}\}$ and
$\Omega_u = \{u \mid -1 < \theta < 1;\ 0 < Y < 1\}$;
i.e. $\|\hat{f}(x) + \hat{g}(x)u - \hat{f}(\hat{x}) - \hat{g}(\hat{x})u\| \le \Lambda \|x - \hat{x}\|$, with Lipschitz constant $\Lambda \in \mathbb{R}$ and $x, \hat{x} \in \Omega_x$. This is due to the physical limitations and the upper-level control of the propulsion system. It is designed to keep the signals (n, θ) inside certain boundaries (corresponding to Ω_x) to achieve desired operation and to avoid overload situations for the shaft and the pitch. Furthermore, there are the following physical limitations: The pitch signal is physically limited by construction $-1 < \theta < 1$ like the fuel index $0 < Y < 1$. The ship speed U is limited by the top speed of the ship. The shaft speed n is limited by an emergency shut-off.

Subsystem (12) and (13) is observable over the complete operating range Ω_x. This can be seen when looking at the system and its corresponding observability codistribution (Nijmeijer and van der Schaft, 1990, Theorem 3.32). The observability codistribution can be obtained as follows (Nijmeijer and van der Schaft, 1990):

$$d\mathcal{O}(x) = \text{span}\{dH(x)|H \in \mathcal{O}\}, \quad x \in \Omega_x$$

where the observation space $\mathcal{O}(x)$ denotes the linear space (over $\mathbb{R}$) of functions on Ω_x containing $h(x)$, and all the repeated Lie derivatives

$$L_{X_1} L_{X_2} \cdots L_{X_k} h_j(x), \quad j \in \mathbf{l},\ k = 1, 2, \ldots$$

with X_i, $i \in \mathbf{k}$, in the set of $\{f, g_1 \ldots g_m\}$. For the considered subsystem it can be seen that

$$dh(x) = (0 \quad 1)$$

$$dL_f h(x) = \Bigg(\frac{1-t_T}{m} T_{|n|U} U \qquad \frac{1}{m}\frac{\partial R(U)}{\partial U} + \frac{1-t_T}{m} T_{|n|U} n \Bigg)$$

$$\Rightarrow \dim d\mathcal{O}(x) = 2 = n = \dim \Omega_x \quad \text{for} \quad u \in \Omega_u$$

Hence, the subsystem is observable over the complete operating range Ω_x.

Using the facts that $\hat{f}(x) + \hat{g}(x)u$ is globally Lipschitz, the subsystem (12) and (13) is observable over the complete operating range Ω_x, and that the inputs are bounded ($u \in \Omega_u$) the stability of the proposed observer can be proven by using the result of (Gauthier *et al.*, 1992). In (Gauthier *et al.*, 1992) it is also shown how the observer gain K has to be chosen. For the simulations in the following it is chosen *ad hoc.*

6. SIMULATION RESULTS

The obtained observer (14) and (15) is implemented and the residual is shown in figure 1. A sample sequence of 600 sec. from the total sequence of 3500 sec. is sufficient to illustrate the applicability of the observer. Measurement noise is not simulated to enhance visibility. The residual is generated as:

$$r = U_m - \hat{U}$$

where $\hat{U}$ is the observer output. The gains and initial conditions are chosen as:
$K^{\hat{n}}_{\Delta k_y} = 0.001$, $K^{\hat{U}}_{\Delta k_y} = 0.01$, $\hat{n}(t=0) = 9\ rad/s$, and $\hat{U}(t=0) = 0.1\ m/s$.
The shaft speed measurement fault as well as dynamic transient effect due to fast change in set-points is shown to have minimum impact on the residual. Their effect can be handled by choosing an appropriate threshold. The gain fault can be detected within the required *time-to-detect* proposed in (Izadi-Zamanabadi and Blanke, 1998). Measurement noise can be dealt with by using statistical methods such as CUSUM.

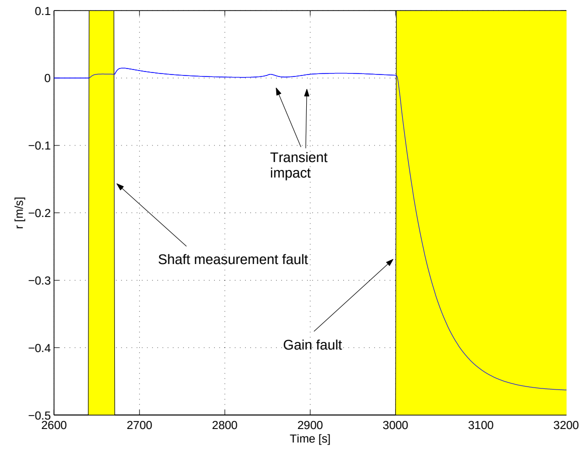

Fig. 1. Residual, $r = U_m - \hat{U}$. Both the shaft speed measurement and gain fault are present.

7. CONCLUSIONS

This paper briefly reviewed the algorithms used for a geometric approach to nonlinear fault detection and isolation. A ship propulsion system was used to illustrate its applicability. As a result a subsystem was obtained that is only affected by the diesel engine gain fault. A diagnostic nonlinear observers for the obtained subsystem was constructed. Simulation results showed that in contrast to earlier published results (Åström *et al.*, 2000, Chapter 13) the gain fault could be detected and isolated from the shaft speed measurement fault by using the nonlinear observer. However, the detection is slower, because the result is based on the ship speed dynamic which is significantly slower than the shaft speed dynamic used in other existing approaches. The results illustrate the strong ability of the geometric approach to analyze a system in a systematic way. As a result, dedicated subsystems are extracted under certain conditions that can be used for observer-based FDI.

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