International Journal of Rotating Machinery
1999, Vol. 5, No. 3, pp. 203–218
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Transformation of Gear Inter-Teeth Forces into Acceleration and Velocity*

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(Received 23 April 1998; In final form 10 July 1998)

The paper deals with mathematical modelling and computer simulation of a gearbox system. Results of computer simulation show new possibilities of extended interpretation of a diagnostic acceleration signal if signal is obtained by synchronous summation. Four groups of factors: design, production technology, operation, change of gear condition are discussed. Results of computer simulations give the relation between inter-teeth forces and vibration (acceleration, velocity). Some results of computer simulations are referred to the results obtained in rig measurements and in field practice. The paper shows a way of increasing the expert's knowledge on the diagnostic signal, which is generated by a gearbox system, on a base of mathematical modelling and computer simulation.

Keywords: Gearing diagnostic, Vibration, Computer simulation, Condition factors, Inter-teeth forces

1. INTRODUCTION

Mathematical modelling and computer simulation give new possibilities of investigating the vibration diagnostic signals generated by a gearing of gearbox system for aiding diagnostic inference. In Bartelmus (1994, 1996, 1997), relations between condition of the gearing and inter-teeth forces are given. It comes from that the results of computer simulations were referred to results obtained by measurements presented in Rettig (1977). Because the diagnostic assessment of the gearing condition is taken from vibration measurements, the presented paper is mainly concentrated on relation between inter-teeth forces and vibration parameters like acceleration and velocity. Simulations may be done for any conditions which may change the vibration diagnostic signal. Gear conditions under which investigations were done by Rettig were limited to the change of the operation caused by the change of rotation speed of gears. The gear conditions may be described, as stated in Bartelmus (1992), by four groups of factors: design, production technology, operation, change of gear condition. Many factors will be taken into consideration and results of computer simulations given by the

* This paper was originally presented at ISROMAC-7.
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relation between inter-teeth forces and vibration (acceleration, velocity) will be presented. First mathematical model of a gear system taken into consideration design, production technology, operation and change of condition was given in Bartelmus (1994). The mathematical model is constantly developed and by the use of computer simulations different aspect of gear system dynamics are investigated (Bartelmus, 1996; 1997). The results of computer simulations are referred to the results obtained by a rig investigation (Rettig, 1977) and a field investigation (Bartelmus, 1988; 1992). The results obtained by Rettig (1977) are given in Fig. 1. A dynamic factor giving as a ratio $K_d = F(t)/F$ against a length of line of action, expressed by % of the length, is given. A gear system may run under resonance and over-resonance. The gear system operates at resonance when a meshing frequency equals to a natural frequency of a gearing. Results of computer simulations are given in Figs. 2–4. In Fig. 2 the result of computer simulation is given for the gearing operation under resonance run. It is easy to see similarities obtained by measurements and computer simulations, compare Fig. 1 with Fig. 2, run under resonance. A result of computer simulation when gearing runs at resonance is given in Fig. 3. In Fig. 3 one can see a

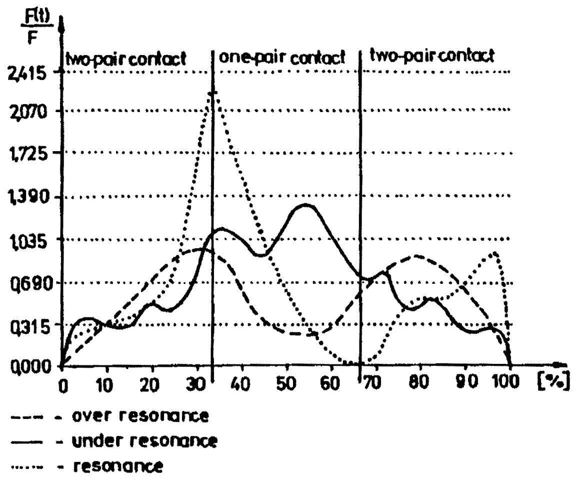

FIGURE 1 Results of measurements of inter-teeth forces (Rettig, 1977).

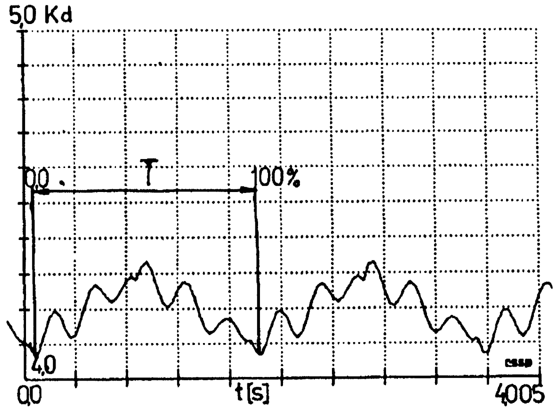

FIGURE 2 Function of gearing dynamic factor K_d for under resonance run of gearing (Bartelmus, 1996), T – meshing period.

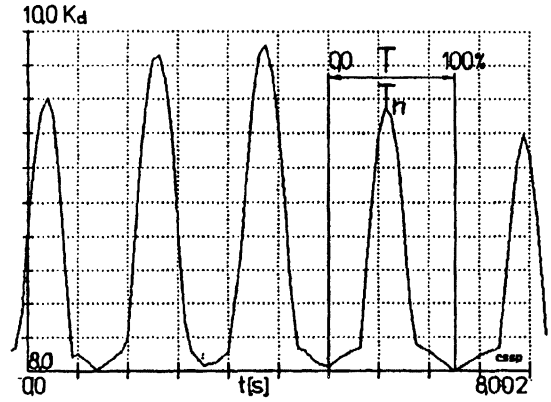

FIGURE 3 Function of gearing dynamic factor K_d for resonance run of gearing (Bartelmus, 1996), T – meshing period, T_n – natural vibration period.

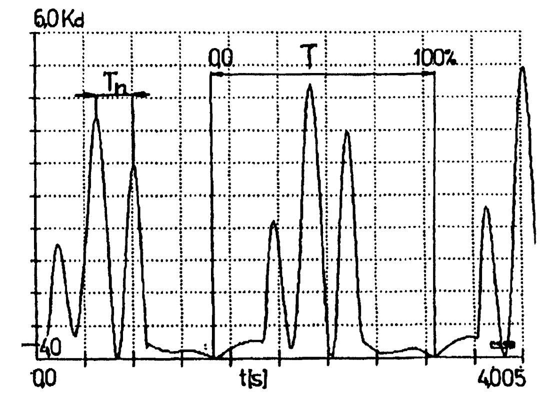

FIGURE 4 Function of gearing dynamic factor K_d for unstable run of gearing (Bartelmus, 1996), T – meshing period, T_n – natural vibration period.

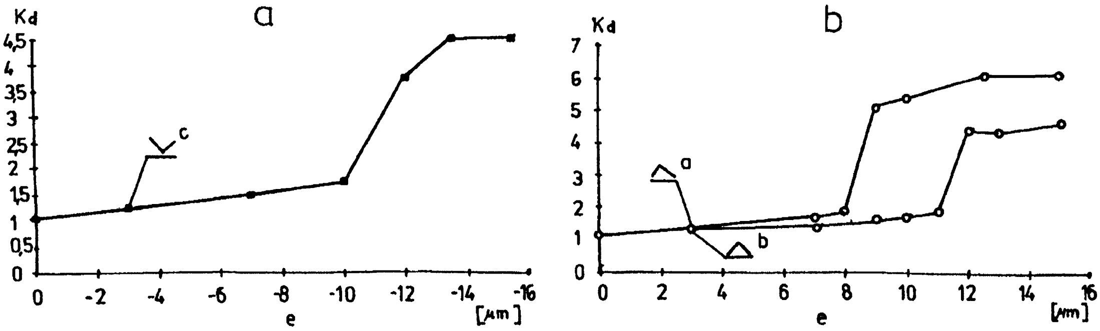

FIGURE 5 Gearing dynamic factor K_d as function of inter-teeth error and shape of error (Bartelmus, 1996), (a) error mode $(a; e; r)$ (parameter of error function; maximum value of error; coefficient of error change), $(0.1; e; 0)$, (b) error mode for $(0.5; e; 0)$, (c) error mode for $(0.5; -e; 0)$.

distinct pick for one period of meshing the same as for a result taken from measurements (Fig. 1). Figures 1–3 describe the influence of operation factors to a signal generated by a gearing. The co-operation of a gearing depends also on the design and the change of condition factors given by errors of teeth. Figure 4 gives a result of computer simulation when a gearing runs at unstable conditions caused by tooth errors (Bartelmus, 1996). Figure 4 shows influence of a natural frequency to a course of inter-teeth forces. In Fig. 4 a period of a meshing (0.0–100%) and period T_n of a natural frequency is given. Figure 5(a) and (b) shows courses of K_d against error e (μm) and as the function of error shape, defined later. Presented results of computer simulations are also referred to the results presented in Penter (1991) where diagnostic signal is obtained by synchronous summation. An example of a vibration signal is given in Fig. 6 (Penter, 1991). The signal is given as a function of time t (s). It is the signal that shows a broken tooth in the gearing. Presented results of computer simulations may be considered as idealised results of synchronous summation.

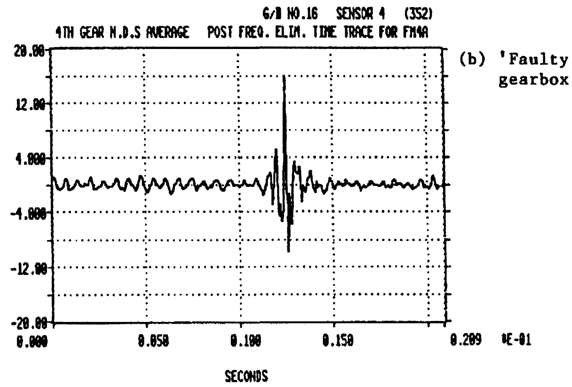

FIGURE 6 Diagnostic signal for broken tooth obtained by synchronous summation of signal (Penter, 1991).

2. MODELLING OF GEARBOX SYSTEM

As it was stated for modelling of dynamic properties of gear system: design, production technology, operation, change of gear condition factors ought to be considered. Design factors include specified flexibility/stiffness of the gear components, especially flexibility/stiffness of a meshing, and a specified machining tolerance and errors of components.

Production technology factors include deviations from specified design factors obtained during machining and assembly of a gearbox.

Operational factors include peripheral speed (pitch line velocity) v (m/s) and its change Δv (m/s) and load F and its change ΔF.

Change of condition includes influences of gear wear, pitting, fractured or broken tooth.

From simulation point of view in the considered gear system the design factors can be divided into two groups: constant and controlled. The constant design factors are not controlled/changed for different simulation experiments. The controlled design factors are changed before a specified simulation experiment. The constant design factors are given by: I_s, I_{1p}, I_{2p}, I_m – moments of inertia (kg m^2) (Fig. 7); k_1, k_2 – shaft stiffness coefficients (Nm/rad) (Fig. 7); μ – coefficient of inter-teeth friction; C_h – gearing damping coefficient (N s/m); r_1, r_2 – base radii of gears (m); a, b, c – parameters of gearing stiffness (0–1) (Fig. 8(a)); l – inter-teeth backlash µm; C – maximum value of gear stiffness (N/m), g – changeability of gearing stiffness (0–0.4), 0.4 for spur-gear. The controlled design factors are given by: C_s – clutch/coupler dumping coefficient (N m s/rad); a, e_1 – parameters of error function (Fig. 8(b)); l_i – random coefficient of error (0–1); r – coefficient of error change (0–1), so a value of an error for a given tooth is expressed by

$$e = [1 - r(1 - l_i)]e_1, \tag{1}$$

where i – number of teeth pair; l_i is distributed randomly for z_1 pair of teeth, number of teeth in the pinion of gears equals to z_1, e_1 maximum value of teeth error (µm). The error of teeth may be described by error mode $(a; e_1; r)$. Mathematical model for torsion vibration for the system (Fig. 7(a)), is given by equations

$$\begin{aligned} I_s\ddot{\varphi}_1 &= M_s(\dot{\varphi}_1) - (M_1 + M_h), \\ I_{1p}\ddot{\varphi}_2 &= M_1 + M_h - r_1(F + F_t) + M_{tz1}, \\ I_{2p}\ddot{\varphi}_3 &= r_2(F + F_t) - M_2 - M_{tz2}, \\ I_m\ddot{\varphi}_4 &= M_2 - M_r. \end{aligned} \tag{2}$$

Values of forces and moments are given by

$$\begin{aligned} &M_1 = k_1(\varphi_1 - \varphi_2), \qquad M_2 = k_2(\varphi_3 - \varphi_4), \\ &M_h = C_s(\dot{\varphi}_1 - \dot{\varphi}_2)F \; - \; \text{Eq. (4)}, \\ &F_t = C_h(r_1\dot{\varphi}_2 - r_2\dot{\varphi}_3), \end{aligned} \tag{3}$$

where $\varphi, \dot{\varphi}, \ddot{\varphi}$ – rotation angle, angle velocity, angle acceleration; $M_s(\dot{\varphi})$ – electric motor driven moment characteristic; M_1, M_2 – moments of shafts stiffness; I_s, I_m – moments of inertia for electric motor and driven machine; M_h – damping moment of coupler; F, F_t – stiffness and damping inter-teeth forces; M_{tz1}, M_{tz2} – inter-teeth moment of friction, $M_{tz1} = T_1\rho_1$; $M_{tz2} = T_1\rho_2$, where T_1 inter-teeth force of friction (Fig. 7(b)).

Numeric solutions of differential equations are done by CSSP (Continuous System Simulation Program) (Siwicki, 1992) by using England procedure of integration. This is a general procedure of Runge–Kutta type. The procedure assures stability

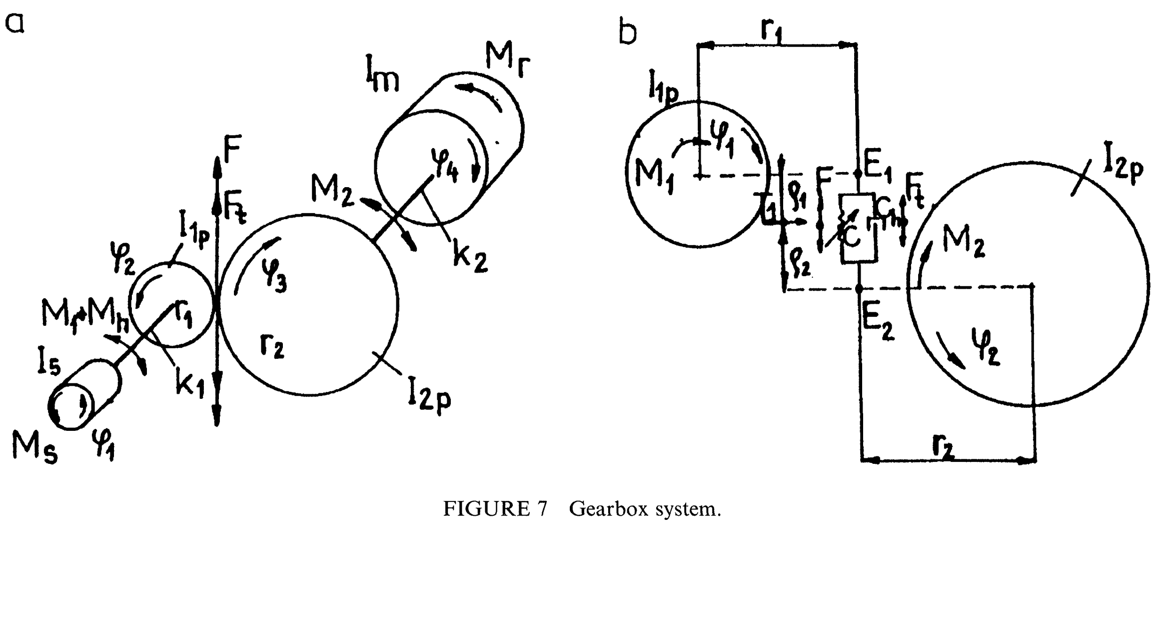

FIGURE 7 Gearbox system.

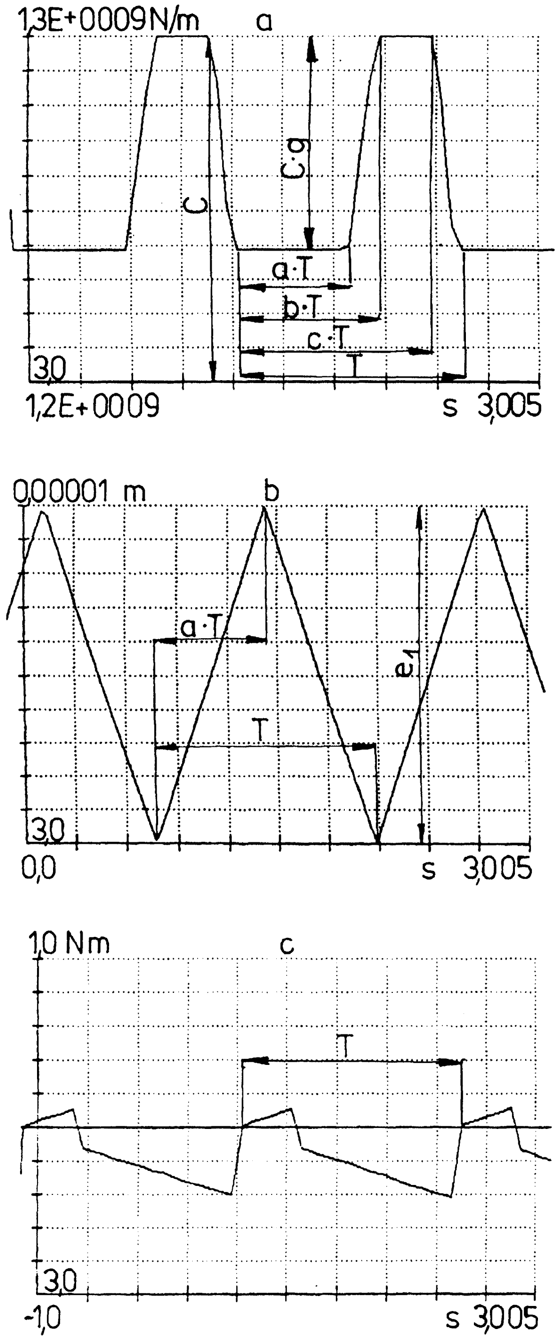

FIGURE 8 (a) Gear stiffness function, T – meshing period, C – gearing stiffness, (a, b, c, g) – parameters of gear stiffness function. (b) Gear error function, T – meshing period, (a, e_1) – parameters of gear error function. (c) Inter-teeth moment of friction function M_{tz1}, T – meshing period.

of integration even in the case of discontinuity and gives possibility of error estimation and the automatic change of an integration step. Unit CSSPEQ (equation) for inclusion differential equations in PASCAL is used. For example the inter-teeth stiffness force can be written in a form

$$
\begin{aligned}
F :=\ & \mathrm{Csz(pom, g)^*(max(r1^*y[6] - r2^*y[7] - l}\\
& \mathrm{+ Er(pom, a, e1)), min(r1^*y[6] - r2^*y[7]}\\
& \mathrm{+ l + Er(pom, a, e1), 0)));}
\end{aligned} \tag{4}
$$

where Csz(pom, g) – stiffness function; max and min functions are defined as follows:

```
Function min(a, b:real):real;
  Begin
    if a < b then min := a else min := b
  End;                                        (5)
Function max(a, b:real):real;
  Begin
    if a > b then max := a else max := b
  End;
```

r1; r2 – gear base radii; l – inter-teeth backlash; y[6] = φ_2; y[7] = φ_3; Er(pom,a,el) – error function, where pom := frac(y[6]*z1/(2*PI)); a, e1 – parameters of error function; z1 – number of teeth in a pinion.

3. RESULTS OF COMPUTER SIMULATIONS

Controlled factors which were changed for investigating their influence to diagnostic signal are: C_s – clutch/coupler dumping coefficient, a – parameter of the error function (Fig. 8(b)), and r – coefficient of error change (0–1), Eq. (1). Obtained results of computer simulation are interpreted like results obtained by synchronous summation of a diagnostic signal. First set of results of computer simulations is given in Fig. 9. Figure 9(a) gives a picture of K_d function in four different periods: (1) acceleration of a gear system (Fig. 7), from 0 to 980 rpm; (2) free rotation; (3) run of the gear system

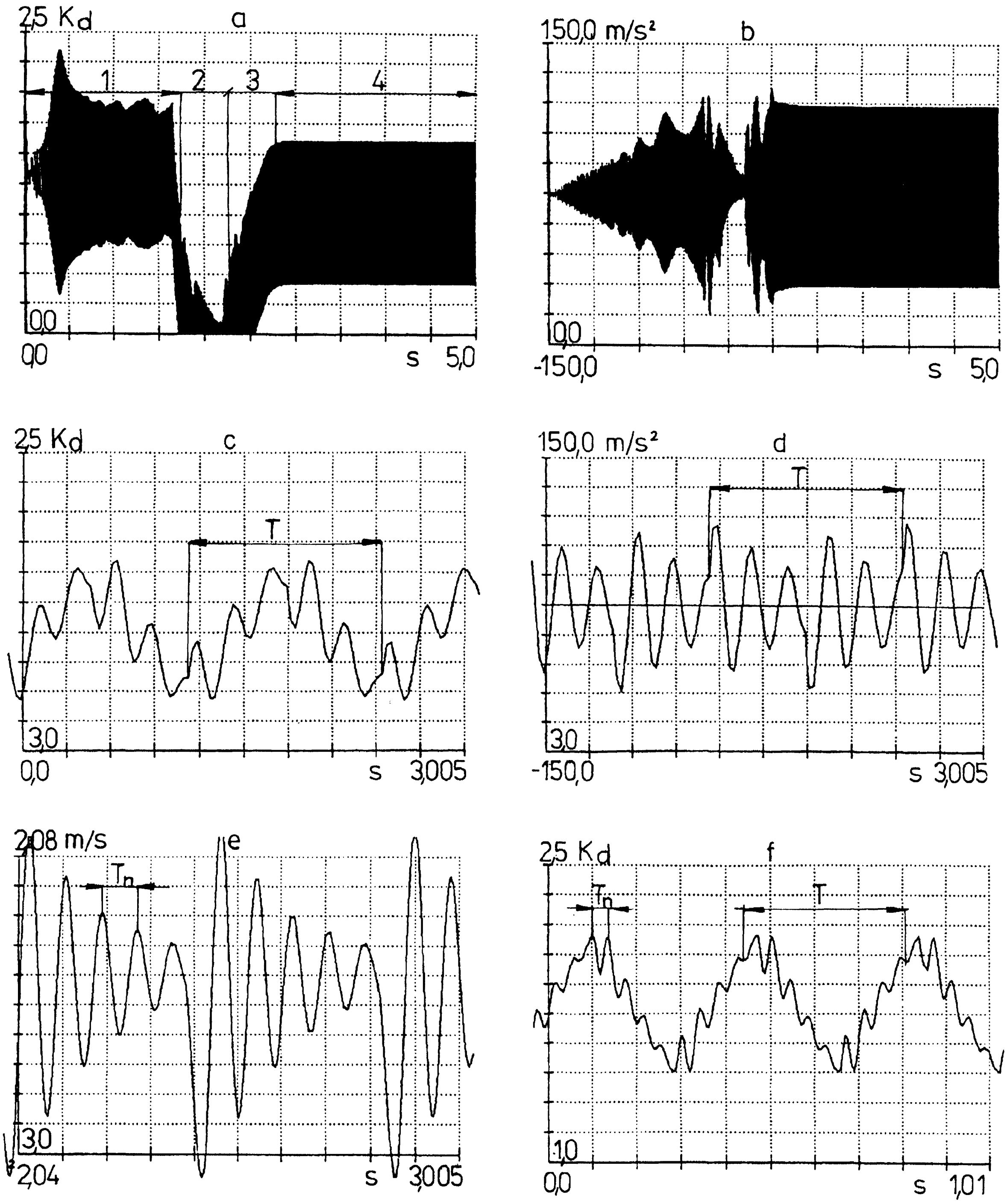
2,5 Kd
a
1
2
3
4
0,0
0,0
s
5,0
150,0 m/s²
b
0,0
-150,0
s
5,0
2,5 Kd
c
T
3,0
0,0
s
3,005
150,0 m/s²
d
T
3,0
-150,0
s
3,005
2,08 m/s
e
Tn
3,0
2,04
s
3,005
2,5 Kd
f
Tn
T
1,0
0,0
s
1,01

FIGURE 9(a)–(f)

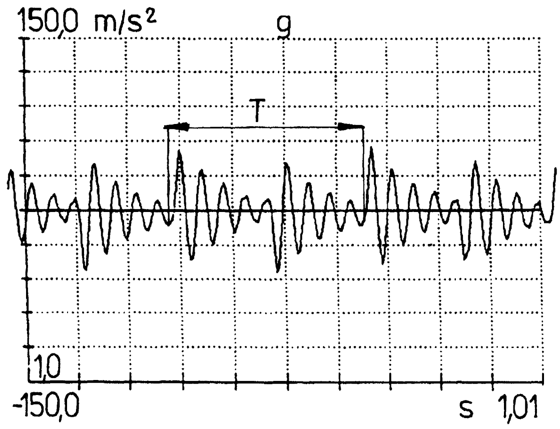

FIGURE 9(g)

FIGURE 9 (a) Function of gearing dynamic factor K_d, 1 – period of acceleration of gear system from 0 to 980 rpm, 2 – period of free rotation, 3 – period of run under linear increase of outer moment, 4 – period of run under constant outer moment. (b) Function of gearing circumference acceleration Δ_a; (c) Zoom of K_d, stable run of gearing under steady load, 4th period. (d) Zoom of gearing circumference acceleration function Δ_a, 4th period. (e) Zoom of gearing circumference velocity Δ_v, 4th period. (f) Zoom of K_d, unstable run of gearing during increasing rotation, 1st period. (g) Zoom of gearing circumference acceleration Δ_a, 1st period.

under linear increase of outer moment M_r; (4) run of the gear system under constant outer moment M_r. Inter-teeth forces are the reasons which cause the failure of a gearing. The inter-teeth force reveals all factors which have influence to vibration generated by a gearbox. The forces are transmitted through bearings to an outer housing. A direction of transmission of inter-teeth forces is given in Fig. 7(b) and lies along a line of action E_1E_2. We supposed that if we measure an acceleration on the gearbox housing we may infer on the inter-teeth force's change. It is supposed that the change of the inter-teeth forces is proportional to the difference of acceleration Δ_a of co-operating gear wheels. The main aim of a computer investigation is presenting differences or similarities between force and acceleration Δ_a. Inter-teeth forces are presented as a ratio K_d. Figure 9(b) gives the acceleration difference Δ_a in four periods. In Fig. 9 results for the error mode (0.5; 10; 0) are given. The error mode function is given in Fig. 8(b). Figure 9(c) gives K_d function in 4th period of a gear system run. In Fig. 9(d) Δ_a acceleration is given. One can see similarities between Fig. 9(c) and (d). For the same period of time velocity difference Δ_v is given in Fig. 9(e). There is no direct similarity between inter-teeth force and velocity Δ_v. Inter-teeth force function for 1st period of gearing co-operation is given in Fig. 9(f). The function shows the period of gearing and the period of natural vibration of gearing T_n. The function of acceleration Δ_a for the 1st period is given in Fig. 9(g). One can see that the error function given in Fig. 8(b) is a cause of two vibration impulses (increase and decrease), so a meshing period T is divided into two periods. It is better seen in acceleration function Δ_a than in the force function (Fig. 9(f)). Figure 9(c) and (d) does not show full similarity (forces to acceleration), it is supposed that a cause of it is influence of damping moment in the clutch, M_h so for further investigation $C_s = 0$ is taken. Figure 10 gives results of these simulations for condition of $C_s = 0$. Figure 10(a) gives a course K_d function. Compare Fig. 9(a) with Fig. 10(a). In Fig. 9(a) influence of damping moment M_s is seen. Figure 10(b) gives the zoom of K_d course for $C_s = 0$. A zoom course of accelerations Δ_a presents Fig. 10(c). Figure 10(b) and (c) gives exact similarities of these two courses. Figure 10(d) shows a zoom course of velocity Δ_v for $C_s = 0$ in the 4th period. Physical quantities of K_d and acceleration Δ_a for the 1st period are given in Fig. 10(e) and (f), $C_s = 0$. Figure 10(e) shows different main period of a course of K_d, compare Fig. 9(f) with Fig. 10(e). Figure 10(e) of accelerations Δ_a in its course shows a meshing period T of meshing and the gear natural period T_n. Figure 11 shows characteristic features of diagnostic signal for an error mode (0.1; 10; 0). Figure 11(a) shows an error mode function. Figure 11(b) and (e) shows zooms of inter-teeth forces for 4th and 1st period. Figure 11(d) and (f) shows zooms of acceleration Δ_a. The error mode (0.1; 10; 0) is thought to describe new gearing before run in or at the condition change caused by failure of one bearing supporting gear wheels. At the condition of bearing failure value of e increases either. Compare different courses given in

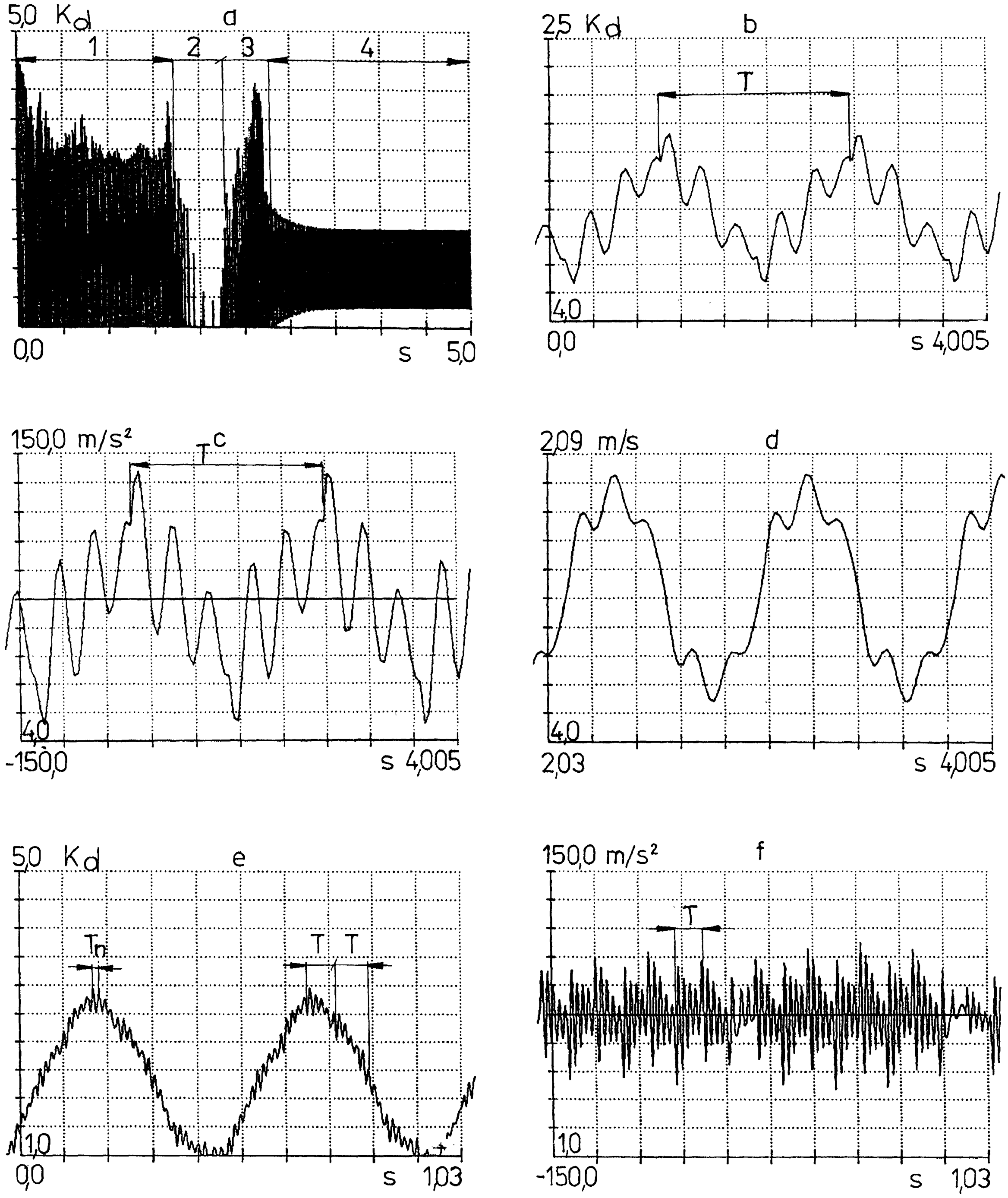

FIGURE 10 (a) Function of gearing dynamic factor K_d, clutch damping $C_s = 0$, 1 – period of acceleration of gear system from 0 to 980 rpm, 2 – period of free rotation, 3 – period of run under linear increase of outer moment, 4 – period of run under constant outer moment. (b) Zoom of K_d for $C_s = 0$, stable run of gearing under steady load, 4th period. (c) Zoom of gearing circumference acceleration Δ_a for $C_s = 0$, 4th period. (d) Zoom of gearing circumference velocity Δ_v for $C_s = 0$. (e) Zoom of K_d for $C_s = 0$, unstable run of gearing during increasing rotation, 1st period. (f) Zoom of gearing circumference acceleration Δ_a, $C_s = 0$, 1st period.

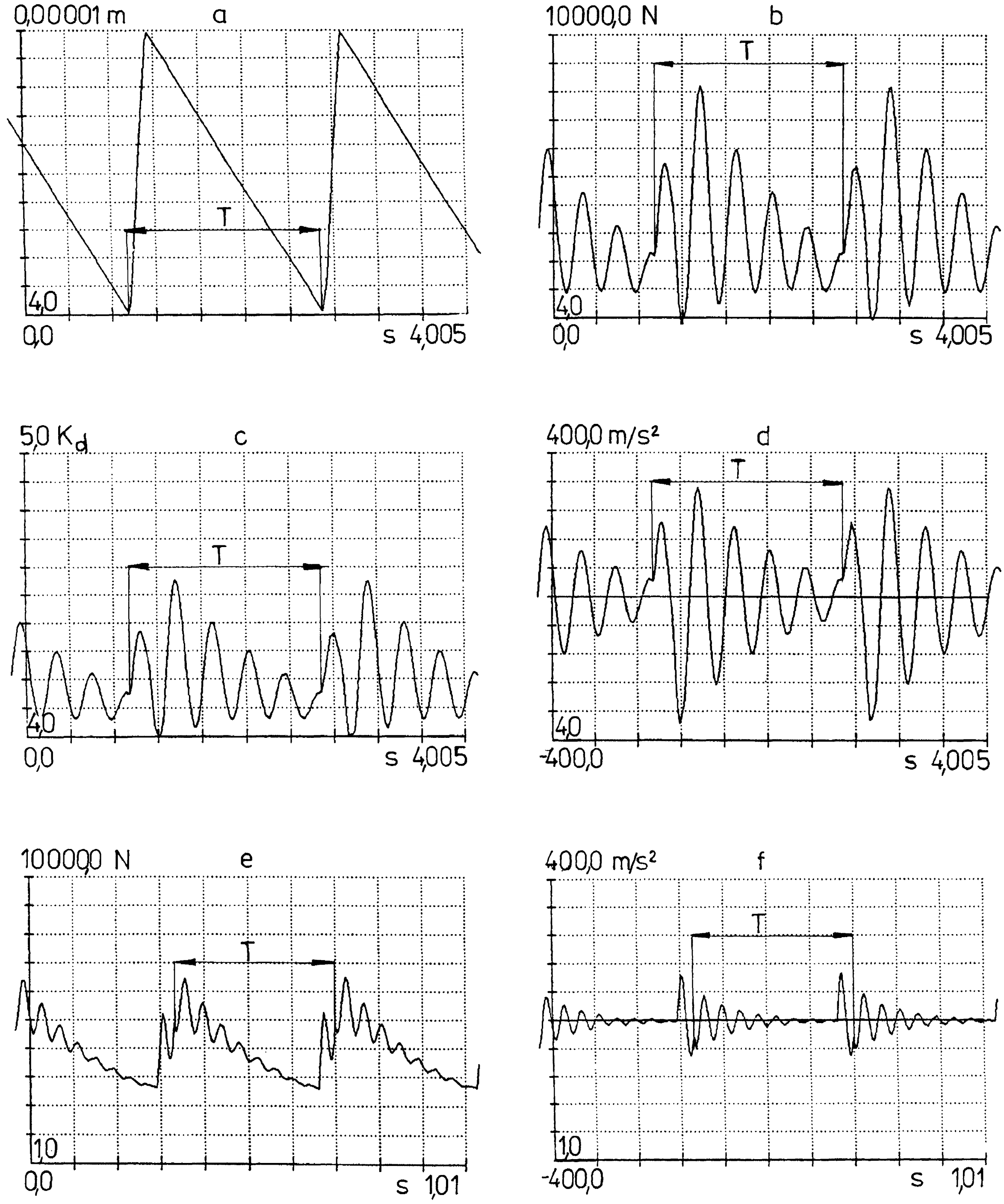

FIGURE 11 (a) Gear error function for error mode $(a; e; r)$ (parameter of error function; maximum value of error; coefficient of error change), (0.1; 10; 0). (b) Zoom of inter-teeth force, parameter of error function $a = 0.1$, stable run of gearing under steady load, 4th period. (c) Zoom of gearing dynamic factor K_d function $a = 0.1$, 4th period. (d) Zoom of gearing circumference acceleration Δ_a, $a = 0.1$, 4th period. (e) Zoom of inter-teeth forces, $a = 0.1$, 1st period. (f) Zoom of gearing circumference acceleration Δ_a, $a = 0.1$, unstable run of gearing during increasing rotation, 1st period.

Figs. 9(g) and 11(f). The meshing period in Fig. 9(g) is divided into two equal parts ($a = 0.5$) in the error mode, in Fig. 11(f) the machine period is divided in different ways ($a = 0.1$) in the error mode. Deterioration of a gearing causes random change of error function. A depth of error change for simulation of this condition is given by an error mode parameter r. Current error is given by Eq. (1). Error functions for $r = 0.1; 0.3; 1$ are given equivalently in Fig. 12(a), (d) and (h). In Bartelmus (1997)

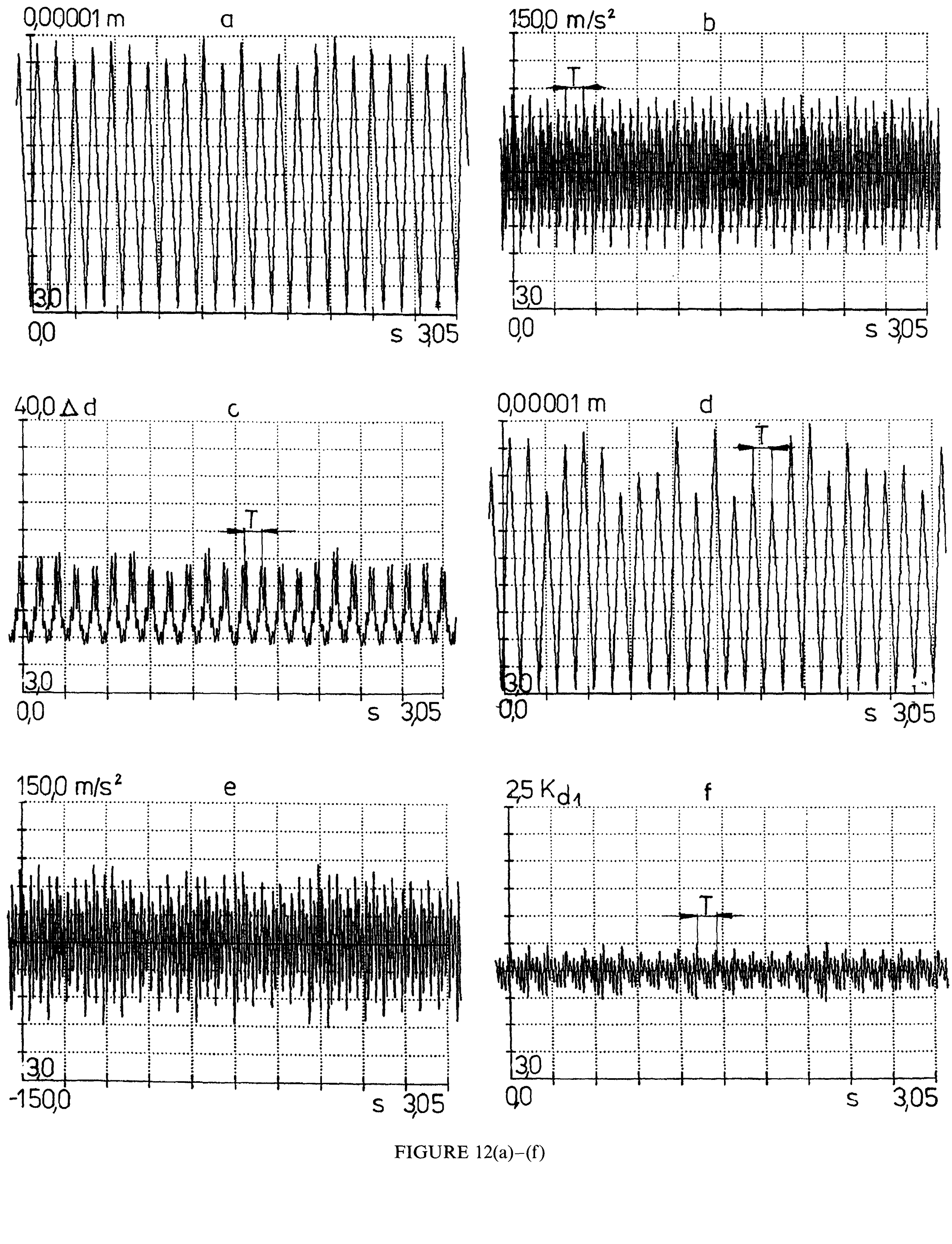

FIGURE 12(a)–(f)

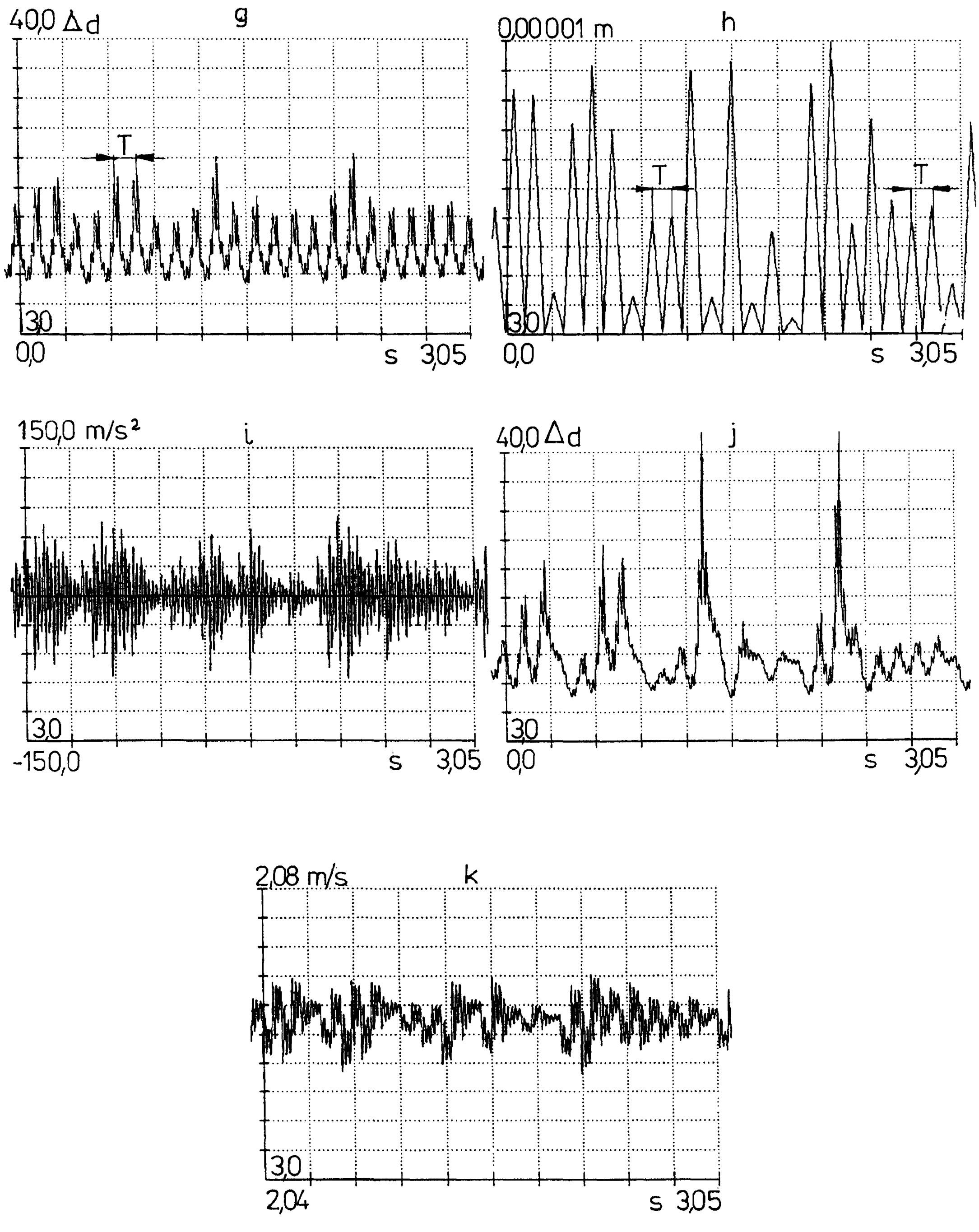

FIGURE 12(g)–(k)

FIGURE 12 (a) Error mode function for (0.5; 10; 0.1), ($a; e; r$) (parameter of error function; maximum value of error; coefficient of error change). (b) Gearing circumference acceleration function Δ_a for coefficient of error change $r = 0.1$, stable run of gearing under steady load, 4th period. (c) Function of acceleration dynamic coefficient A_d for $r = 0.1$, 4th period. (d) Error mode function for (0.5; 10; 0.3). (e) Gearing circumference acceleration function Δ_a for $r = 0.3$, 4th period. (f) Function of current dynamic factor K_{d1} for $r = 0.3$, 4th period. (g) Function of A_d for $r = 0.3$, 4th period. (h) Error mode function for (0.5; 10; 1). (i) Gearing circumference acceleration function Δ_a for $r = 1$, 4th period. (j) Function of A_d for $r = 1$, 4th period. (k) Gearing circumference velocity function Δ_v for $r = 1$, 4th period.

some new normalised functions for evaluation of gearing conditions were discussed. The most suitable function was chosen defined as $K_{d1} = F(t)/F_1(t)$, where $F_1(t)$ – measured current force on an input shaft of a gearbox. But for practice there is a need to define equivalent function based on acceleration which are measured on a gearbox housing. For the new condition measure next value is defined as

$$A_d = [A + (\Delta_a)r_1]/(M_1 + M_h), \tag{6}$$

where A_d – normalised gearing condition function; A – suitable constant to make the value positive; Δ_a acceleration; $(M_1 + M_h)$ moment on the first shaft; r_1 – radius of a pinion gear. A_d function is given for $r = 0.1; 0.3; 1$ in Fig. 12(c), (g) and (j). An example of a function of K_{d1} is given in Fig. 12(f) for $r = 0.3$. Acceleration functions Δ_a are given for $r = 0.1; 0.3; 1$ in Fig. 12(b), (e) and (i). One example of a course of velocity function is given in Fig. 12(k) for $r = 1$. On a base of simulations given in Fig. 12, a conclusion is drawn that A_d function is very good parameter for condition change identification of a gearing. One of the most important thing in condition monitoring is identification of a fractured or broken tooth. Figure 6 shows a local change of the signal, for one broken tooth one local change of a diagnostic signal. So we may say there is one-to-one mapping. Another evidence for this is given in Fig. 9(g) where a decrease and an increase of a tooth error (Fig. 8(b)) are identified by one impulse in a diagnostic signal. But for an error shape given in Fig. 11(a) an identification of a decrease and an increase of a tooth error is not so clearly identified (Fig. 11(e) and (f)). Taking in mind possibilities of one-to-one identification, further simulation experiments were undertaken. Figure 13 gives a set of results of simulation for one fractured tooth for which a stiffness fall to 0.68 of its normal stiffness. As it is seen from the results of simulation there is very little change of a diagnostic signal given by K_d; Δ_a; K_{d1} (Fig. 13(a)–(c)). Results of further simulations when stiffness of one tooth in gearing falls to $0.25C$ are given in Fig. 14. Figure 14 gives a set of results of computer

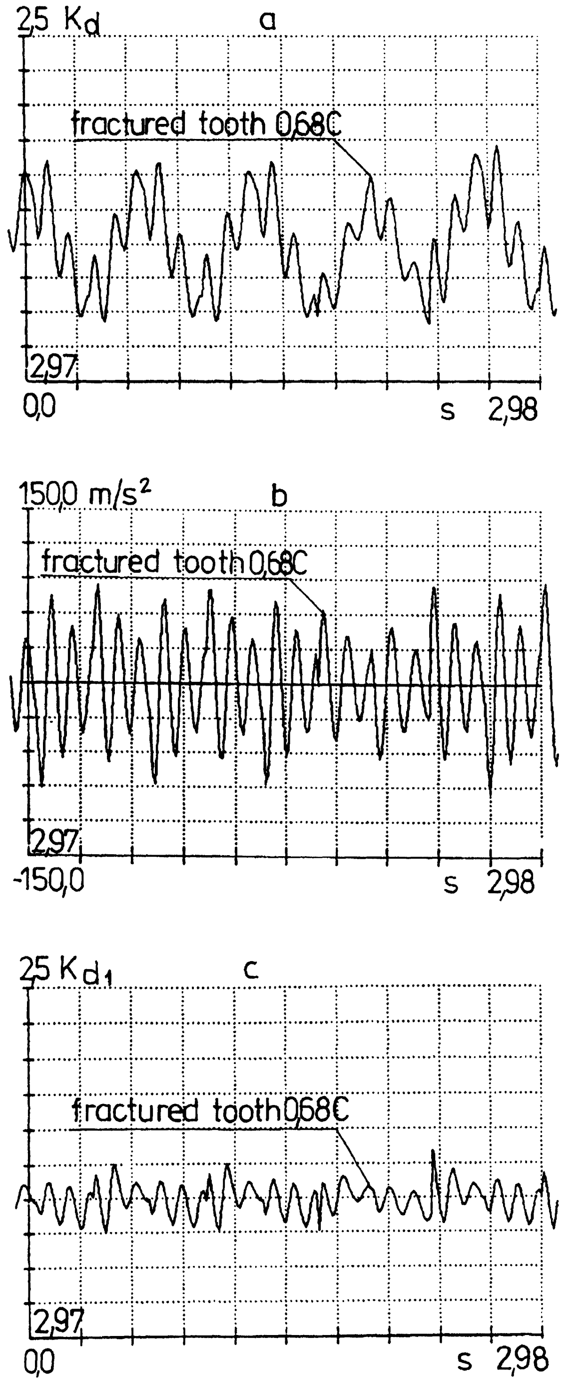

FIGURE 13 (a) Zoom of dynamic factor K_d for gearing stiffness change to $0.68C$. (b) Zoom of gearing circumference acceleration Δ_a for gearing stiffness change to $0.68C$. (c) Zoom of current dynamic factor K_{d1} for gearing stiffness change to $0.68C$.

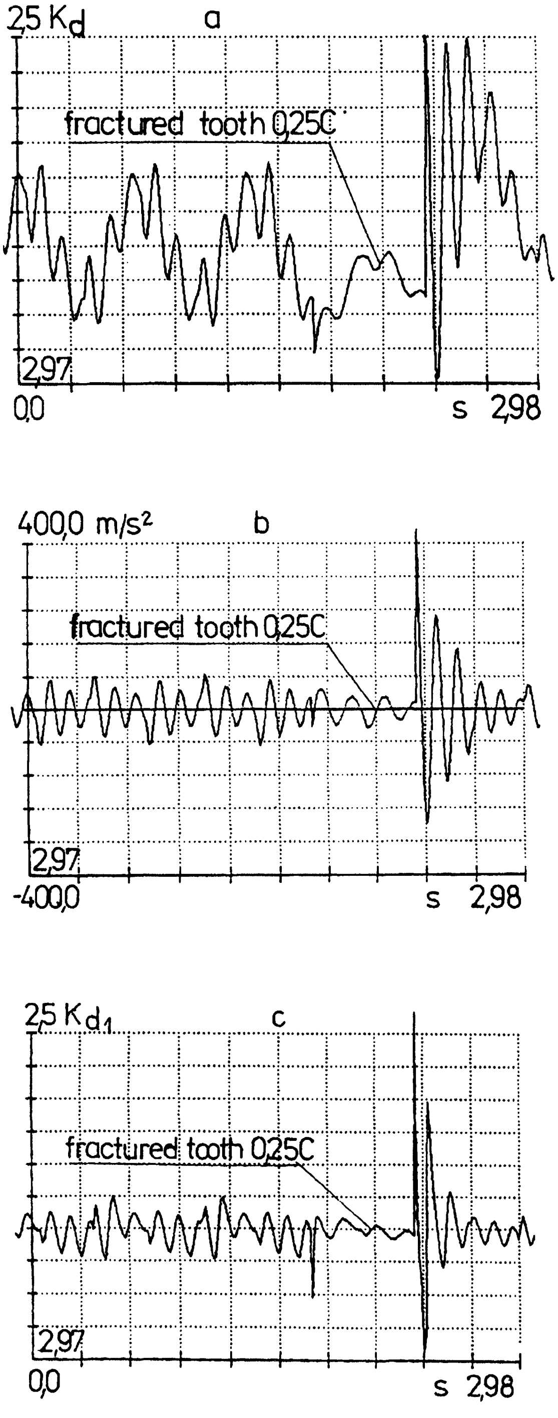

FIGURE 14 (a) Zoom of dynamic factor K_d for stiffness change to $0.25C$. (b) Zoom of gearing circumference acceleration function Δ_a for gearing stiffness change to $0.25C$. (c) Zoom of current dynamic factor K_{d1} for gearing stiffness change to $0.25C$.

simulations for stiffness change to $0.25C$. The results show that the change of stiffness to $0.25C$ gives change of diagnostic signal which may be easy to identify. For further stiffness change to $0.075C$ results are given in Fig. 15. In Fig. 15(a) and (b) one can see one-to-one mapping (one disturbance in the signal one fractured tooth). In Fig. 15(c) it is seen that one fractured tooth may cause disturbance on several teeth, so there is no one-to-one mapping. It may be stated that A_d function defined by Eq. (6) is very sensitive to condition change but for heavy fracture of a tooth function may be too sensitive. A set of simulation results for a broken tooth is given in Fig. 16. The set presents the equivalent zoom functions for K_d; Δ_a; K_{d1}, Fig. 16(c) does not show one-to-one mapping. Figure 17 gives a set of results of

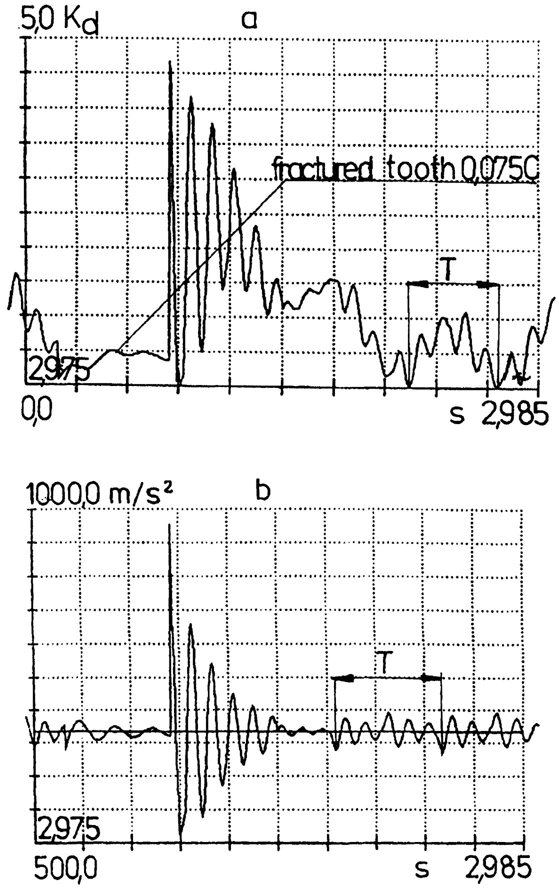

FIGURE 15(a) and (b)

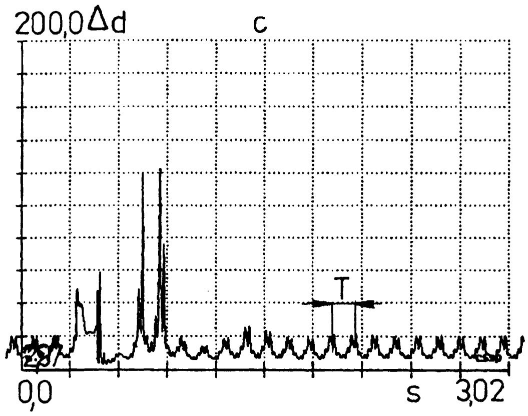

FIGURE 15(c)

FIGURE 15 (a) Zoom of dynamic factor K_d for gearing stiffness change to 0.075C. (b) Zoom of gearing circumference acceleration function Δ_a for gearing stiffness change to 0.075C. (c) Zoom for acceleration dynamic coefficient A_d function for gearing stiffness change to 0.075C.

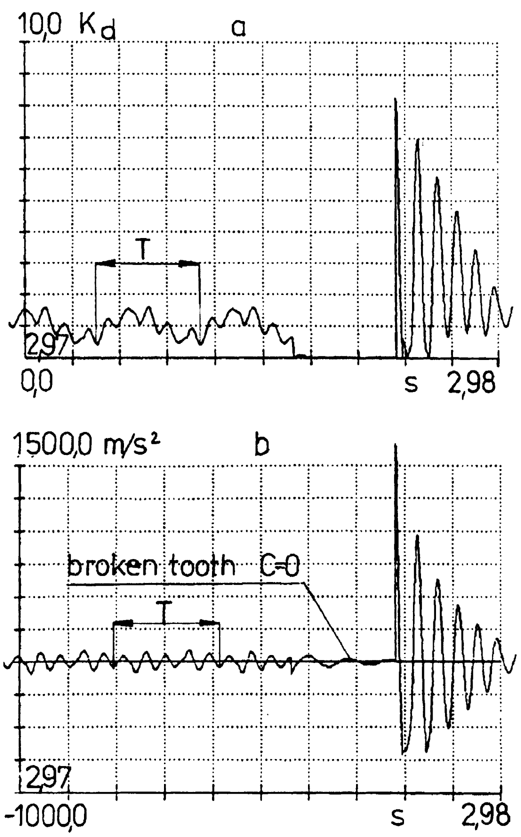

FIGURE 16(a) and (b)

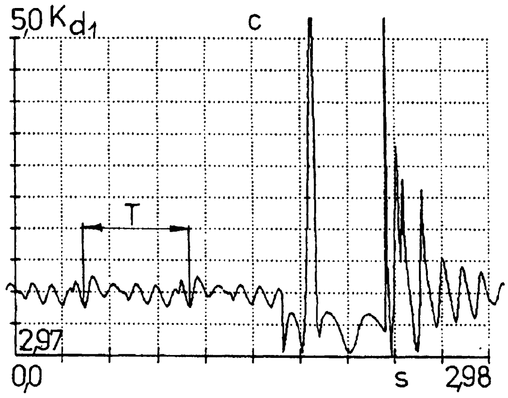

FIGURE 16(c)

FIGURE 16 (a) Zoom of dynamic factor K_d function for broken tooth. (b) Zoom of gearing circumference acceleration function for broken tooth. (c) Zoom of current dynamic factor K_{d1} function for broken tooth.

simulation when one of the tooth has a fault caused by pitting, model of error function is given in Fig. 17(a). Figure 17(c)–(e) shows that there is no one-to-one mapping if diagnostic signal is presented as functions of K_{d1} or A_d.

4. CONCLUSIONS

From the results of computer simulation which are considered as diagnostic signals obtained from synchronous summation detailed features of the signal may be drawn. For example on the basis of results presented in Fig. 2 one may draw a conclusion that an error shape of a tooth taken for investigation by Rettig (see Fig. 1) is as it is given in Fig. 8(b). The same conclusion may be drawn from Fig. 10(c) which gives a diagnostic signal in form of acceleration. From Figs. 9(d) and 10(c) one may draw a conclusion that not only properties of a gearing but also the damping properties of a coupling between an electric motor and a gearbox have influence on a diagnostic signal. One-to-one mapping (one fault one disturbance, in a signal, equivalent for one tooth) does not always hold (see Figs. 15(a) and 16(c)). It seems that this drawback may be eliminated by careful study of evolution/

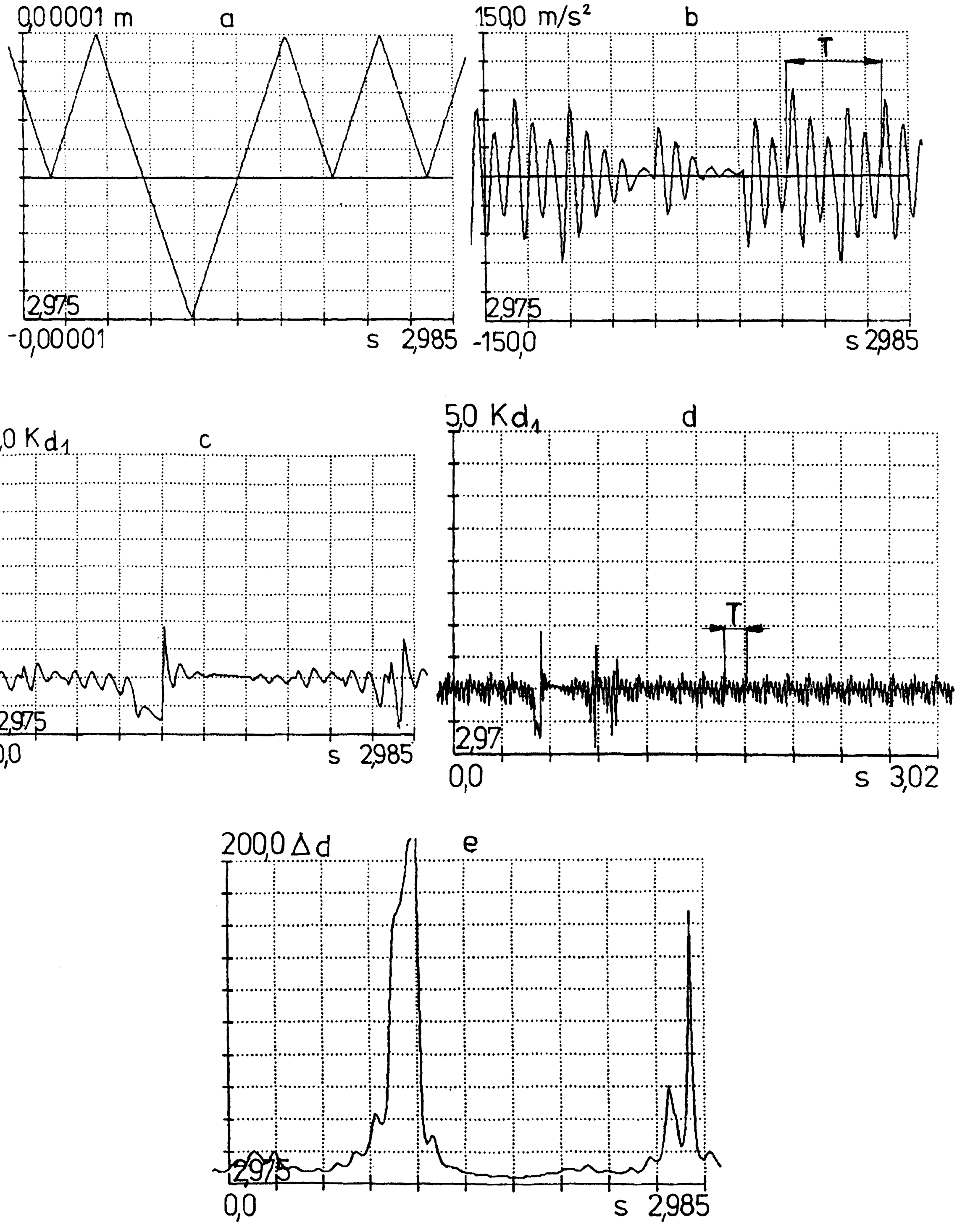

FIGURE 17 (a) Error function for one pitted tooth. (b) Zoom of gearing circumference acceleration function for one pitted tooth. (c) Zoom of dynamic factor K_d function for one broken tooth. (d) Function of current dynamic factor K_{d1} for one pitted tooth. (e) Zoom of gearing circumference acceleration function Δ_a.

development, of a diagnostic signal, as gearing condition changes to avoid misinterpretation. Deterioration of a gearing is described by a change of condition for all teeth in a gearing, models of error modes are given by Fig. 12(a), (d) and (h), and for a single fault, as pitting in one tooth (Fig. 17(a)). The best results of diagnosing the gearing condition change are obtained for signal of acceleration which gives direct measure of inter-teeth forces when a gearbox system runs in steady condition, 4th period of Fig. 9(a). New gearing condition parameter is suggested, the parameter is denoted as A_d and is given by the formula (6). Mathematical modelling and computer simulation is a very good tool for supporting diagnostic inference. Visualisation of diagnostic signals obtained by computer simulation extends knowledge of a diagnostic expert. The presented results show that from signal presented by synchronous summation it is possible to draw many conclusion on gearing condition not only a broken tooth condition.

NOMENCLATURE

a	parameter of error function; parameter of gearing stiffness
A_d	acceleration dynamic coefficient
b	parameter of gearing stiffness
c	parameter of gearing stiffness
C, C_{sz}	gear stiffness, stiffness function (N/m)
C_h, C_s	damping coefficients (N m s or N s/m)
e, e_1	parameters of error function
Er	error function
g	parameter of gearing stiffness
F, F_t	stiffness and damping inter-teeth forces (N)
I_s, I_{1p}, I_{2p}, I_m	moments of inertia (kg m^2)
k_1, k_2	shaft stiffness coefficients (N/m)
K_d, K_{d1}	dynamic coefficients
l	inter-teeth backlash (μm)
l_i	random coefficient of error
M_1, M_2	moments of shaft stiffness (N m)
M_{tz1}, M_{tz2}	inter-teeth moments of friction (N m)
r	coefficient of error change
r_1, r_2	base gear radius (m)
T	inter-teeth friction force (N)
μ	coefficient of friction
Δ_a, Δ_v	acceleration and velocity function (m/s^2 and m/s)
$\varphi_1, \varphi_2, \varphi_3, \varphi_4$	rotation angels (rad)
$\dot{\varphi}$	angle velocity (rad/s)
$\ddot{\varphi}$	angle acceleration (rad/s^2)
ρ_1, ρ_2	radius (m)

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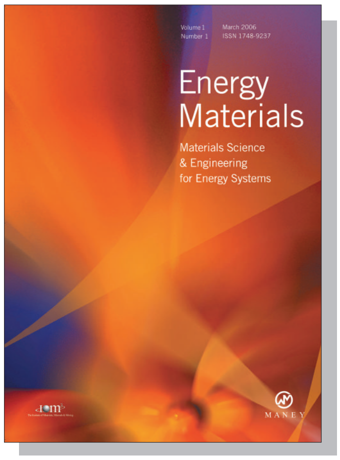

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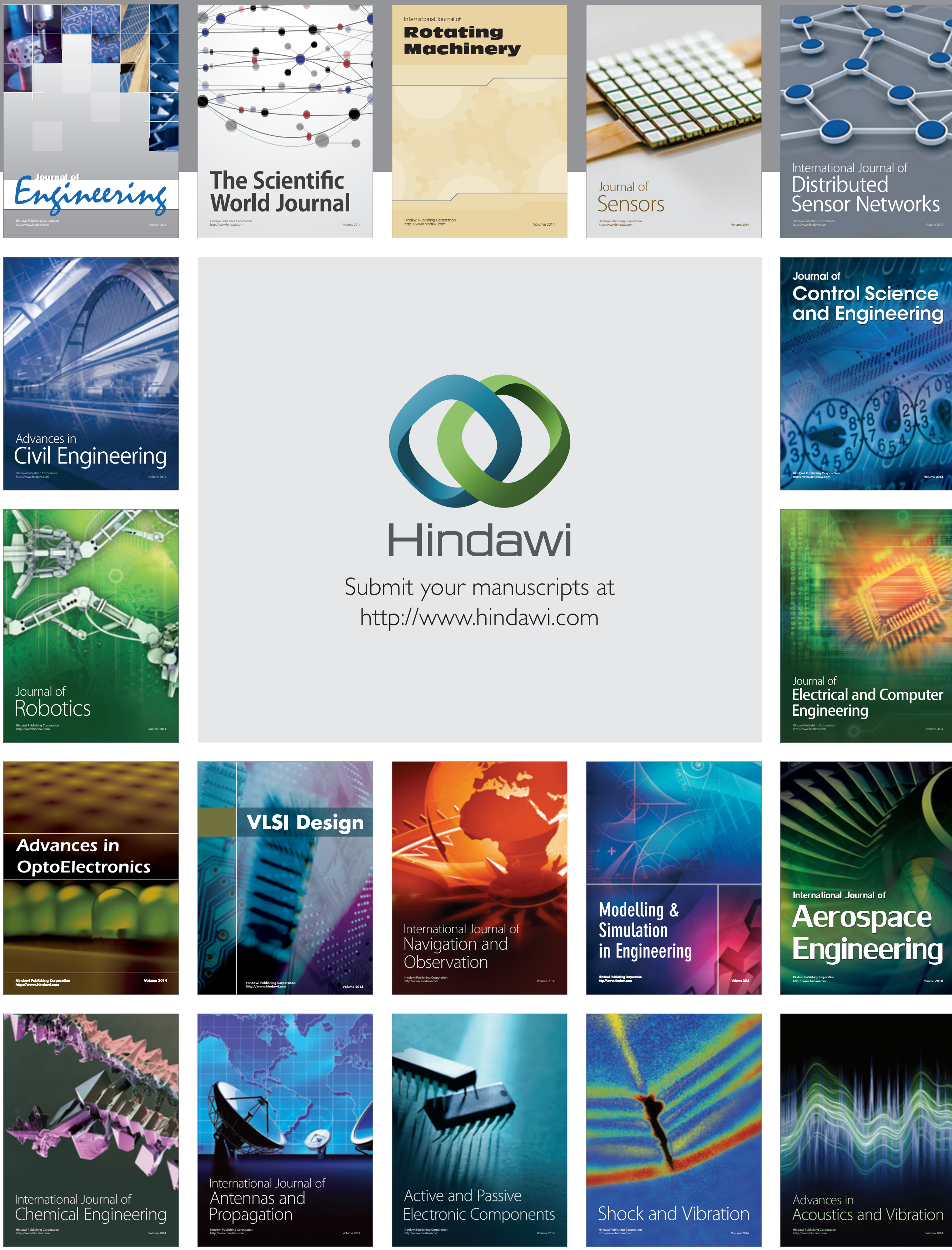

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