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Condition monitoring of multistage printing presses

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Abstract

The main concern in printing quality in multistage presses is *doubling*. Doubling is caused by imperfections either within stages (units) or in links connecting different stages, mainly resulting from machine vibration, gear damage, and excessive run-out. In this paper, we propose new means for printing quality control via geared system health condition monitoring. The diagnosis is based on the signals acquired from inexpensive magnetic pickups. A new technique is developed to monitor the gear rotation synchronization among different stages in order to isolate possible sources of the doubling problem. A new approach is proposed to determine the gear run-out. Moreover, gear tooth damage detection is conducted using the beta kurtosis and the continuous wavelet transform based on the overall residual signal. The beta kurtosis of original signal average is also shown here to be useful in detecting excessive gear run-out. Test results from printing presses demonstrated the viability of the proposed methods.

1. Introduction

A multistage printing press is a complicated and very expensive piece of equipment. Its printing rate (web speed) can be as high as 700 m per minute. A typical press consists of 5–12 printing stages (units), identical in mechanical design. Each unit includes many rollers and cylinders, which are driven by an exposed gear train system housed on the outside of the unit. Fig. 1 schematically shows the main part of a gear system in a unit. Each circle represents a spur or helical gear. The printing cylinder and plate cylinder are connected to gears G7 and G8, respectively. G1 is the input gear. All input gears in each unit are driven either by a long shaft connected to the drive motors or by a separate drive motor in each stage.

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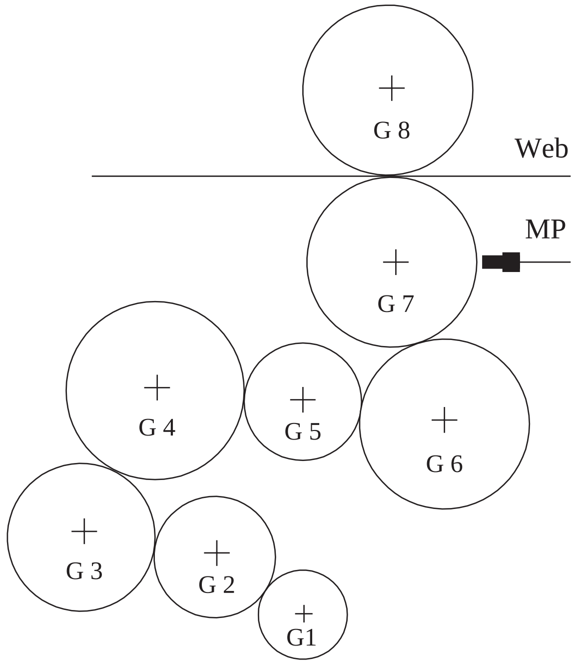


Fig. 1. The gear system in a press unit (stage). Each circle represents a gear pitch circle.

The main concern in printing quality is called doubling, which is a register error among different printing stages (units). It occurs whenever the impression on a printing cylinder blanket does not line up, exactly, with the previous image remaining on the web. Reasons for doubling are related to any rotation non-synchronization among the printing cylinders in different units. It can be caused by imperfections, either within the units or in links connecting different units, resulting from vibration, misalignments, damage and run-out in gears, etc. Electronic compensation systems are utilized, online, in the press to offset some of print imperfections. These offset methods, however, are inadequate to accommodate for inaccuracies caused by machine vibration and the faults in mechanical components. Once the doubling error exceeds a particular threshold, the printing quality falls below tolerance, prompting stoppage to allow for adjustments or repairs. Unfortunately, sometimes it is quite difficult to isolate the sources of the doubling error; some doubling problems are so elusive that they take months or even a year to correct. The machine downtime during inspection and repair may add significant cost to the operation of the press that runs into hundreds of thousands of dollars.

Currently, there are no effective and systematic techniques for the doubling problem diagnoses [1]. In this paper we propose new means to identify the sources of non-synchronization among different units, associated with the mechanical components such as gears and bearings that contribute to the doubling problem. A new vibration analysis method is proposed for rotation synchronization monitoring of the corresponding gears among different units, utilizing the inexpensive and readily available magnetic pickups. We have also developed an approach to determine the gear run-out. Interestingly, it is found that the excessive gear run-out can also be identified from the tooth-based beta kurtosis of the original signal average. Moreover, gear tooth

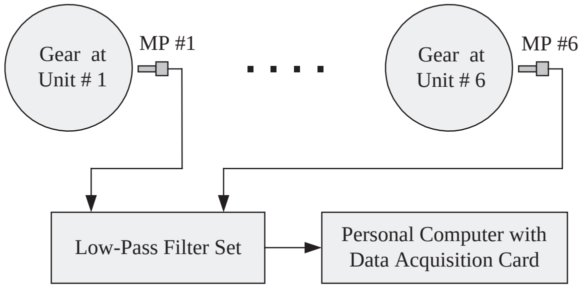


Fig. 2. Data acquisition set-up.

health condition is diagnosed by using the beta kurtosis and continuous wavelet transform, employing the overall residual signal after filtering out the gear meshing frequency and its harmonics. Test results from two multistage printing presses have demonstrated the viability of the proposed techniques.

2. Magnetic pickups

Magnetic pickups (MPs) are generally used as pulse generators for speed switches and digital tachometers. An MP is essentially a coil wound around a permanently magnetized rod. When ferromagnetic objects, such as gear teeth, key-ways, or slotted discs, pass through the probe's magnetic field, its magnetic flux density is modulated, and an AC voltage is induced in the coil. When mounted in the proximity of gear teeth, the MP produces a sinusoidal waveform that is a function of gear rotational speed, tooth dimension and spacing, as well as the air gap between the gear outer circumference and the MP. The polarity of the voltage output depends on whether the target is moving towards or away from the sensor, whereas the signal amplitude is directly proportional to the speed of rotation.

As a non-contacting transducer, compared with other proximity probes, an MP is a self-generating sensor, requiring no external excitation and accessory devices. It has a very low cost, and needs little maintenance. However, in order to get an appropriate signal output, the gear size should not be too small, and the rotational speed should not be too slow. For the MPs used in this test, for example, the required minimum gear module is 1.25 mm, with the threshold surface speed of 750 mm/s.

3. Data acquisition and processing

Experiments presented in this paper are conducted on the press, Quantum 1200,[1] with six printing stages (units). In each unit, one MP is mounted in the proximity of one gear (e.g., gear G7 as shown in Fig. 1). Fig. 2 shows the probes and the data acquisition system. In order to properly apply the MP signal for printing quality monitoring, sufficient samples should be supplied in each revolution, e.g., 32 samples per tooth block in this study. Then the corresponding sampling

[1] Manufactured in 1992 by Sanden Machine Ltd., Cambridge, Canada.

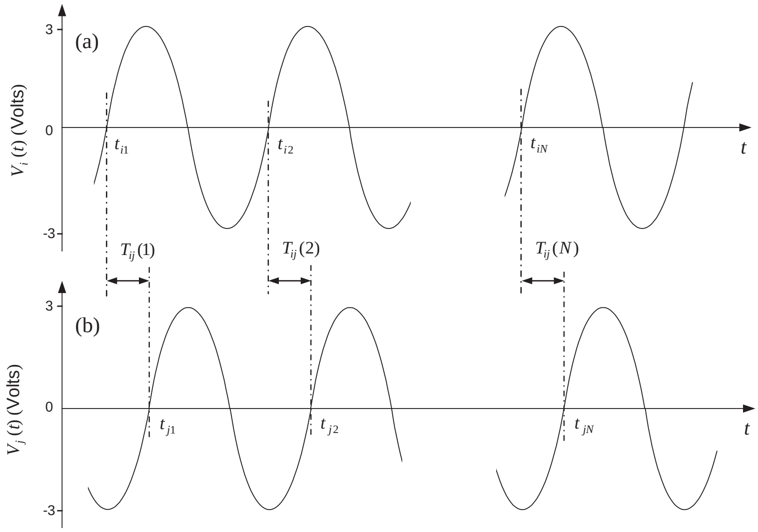


Fig. 3. Part of MP signals: (a) $V_i(t)$ from G7 in unit i, (b) $V_j(t)$ from G7 in unit j.

frequency is $32Nn/60$ Hz, where N is the number of gear teeth, and n in rpm is the gear rotation speed that is determined by the number of revolutions during a specific time interval. $Nn/60$ is referred to as the gear meshing frequency. The signal from each MP is low-pass filtered using a Bessel type filter set, with the cut-off frequency set sufficiently high to capture the fifth harmonic of the gear meshing frequency. The filtered signals are then fed to a PC computer through a data acquisition board. The data are subsequently processed and analyzed in MATLAB®[2] environment.

A software package has been developed in MATLAB specifically for this study for the gear rotation synchronization monitoring, gear run-out detection, as well as gear health condition diagnosis. These data processing techniques are discussed in the following sections.

4. Gear rotation synchronization monitoring

As discussed before, to ensure the required printing quality, all printing cylinders among different stages must operate at exactly the same speed; in other words, the corresponding driving gears in different stages must rotate synchronously without phase variance. But, in practice, due to vibration, gear damage, run-out, and so on, the rotation speed of these gears may vary. When this variation exceeds the tolerance, doubling problem occurs. A gear rotation synchronization detection method is proposed here to isolate the sources of this speed variation.

In each unit, the printing cylinder is driven by gear G7 as shown in Fig. 1. An MP is firstly mounted in each unit in the proximity of gear G7 in the radial direction. For a press with u units, Figs. 3(a) and (b) show parts of MP signals $V_i(t)$ and $V_j(t)$ from units i and j, respectively. Since the MP signal is a tooth-related signature, one tooth in each gear is chosen as the first tooth in one revolution. To simplify the demonstration, only one revolution is considered here. In practical

[2] ®MATLAB is a registered trademark of the MathWorks Inc.

applications, more revolutions are utilized for the analysis, and more than one MP may be applied to each unit.

Choose a specific location in each tooth period, say the zero-crossing position obtained by linear interpolation. The time intervals between the zero-crossings of the corresponding teeth are $T_{ij}(1), T_{ij}(2), \ldots, T_{ij}(N)$, as shown in Fig. 3. The rotation synchronization error (SE) at tooth k, $y_{ij}(k)$, is defined as

$$y_{ij}(k) = \frac{2\pi n}{60}\frac{D}{2}[T_{ij}(k) - \bar{T}_{ij}], n = 1, 2, \ldots, N, \tag{1}$$

where the mean $\bar{T}_{ij} = 1/N \sum_{r=1}^{N} T_{ij}(r)$; n in rpm is the rotation rate of gear G7, and D is the diameter of the gear pitch circle. The SE between the two gears in units i and j, respectively, is

$$SE_{ij} = \{y_{ij}(1), y_{ij}(2), \ldots, y_{ij}(N)\}. \tag{2}$$

Since the higher frequency components in the signal, due to tooth surface roughness for example, do not affect the printing quality significantly, for ease of the pattern classification process, the obtained SE_{ij} in Eq. (2) is low-pass filtered (using a Butterworth filter). From a series of tests, the cut-off frequency is selected as the fundamental gear meshing frequency, i.e., $Nn/60$ Hz.

To prevent excessive rotation (phase) variance between the corresponding printing cylinders in units i and j, each element in Eq. (2) must be within a specific tolerance, i.e.,

$$|SE_{ij}| \leqslant T_d, \quad i,j = 1, 2, \ldots, u, \tag{3}$$

where T_d is the register error tolerance. For the tested presses, $T_d = 0.050$ mm (0.002 in).

If SE_{ij} satisfies Eq. (3), the press is deemed in good printing condition. Otherwise, the doubling problem will be unavoidable. The following example illustrates how to apply the above method to localize the out of order unit/units in relationship to the doubling problem.

The tests in this example are conducted with the help of Quantum 1200. This is an old press with six stages, which has been in use for many years and is to be repaired due to the doubling problem. Fig. 4 shows the synchronization errors, SE_{ij}, relative to gear G7 among units 1–6, respectively. From examining these graphs, it can be seen that gear G7 in unit 2, SE_{i2}, gives the largest rotation synchronization error, followed by SE_{i3}, SE_{i1}, SE_{i4}, SE_{i5} and SE_{i6}, successively. Furthermore, SE_{i2} is out of tolerance (0.05 mm). It can be concluded that unit 2 is most likely the faulty unit that induces the doubling problem due to some imperfections within it. The next step is to identify the sources in unit 2, which result in printing inaccuracies.

Usually there are three main reasons for this excessive doubling error:

(1) Imperfections in location and pressure of the blanket on the printing cylinder. Through inspection, these were found not to be the reason in this case.
(2) Input errors in the transmission systems, i.e., the rotation synchronization errors among gears G1 in different units. This error can be induced by two possible causes: (a) if a press uses a centralized driving system, it may be the faults in the links connecting unit 2 to others due to shaft defects and torsional vibration; (b) if a press uses separate drive system in different units, the error may be induced by the electric motor and feedback systems. By positioning MPs around gears G1, and repeating the test and analysis using the proposed technique, it was found that the rotation SEs among gears G1 were within tolerance (0.050 mm). Accordingly, input errors were not the reason for the doubling problem in this case.

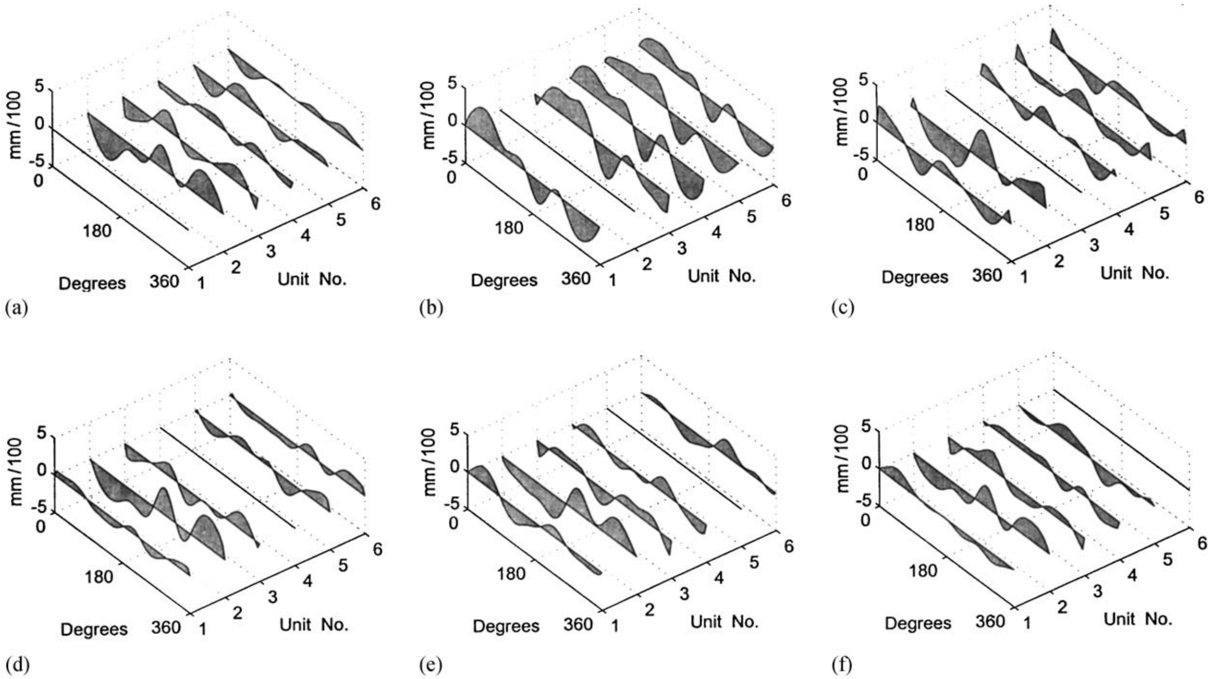


Fig. 4. Rotation synchronization errors: (a) SE_{i1}; (b) SE_{i2}; (c) SE_{i3}; (d) SE_{i4}; (e) SE_{i5}; (f) SE_{i6}; relative to gear G7 in the units 1–6, respectively.

(3) Gear system faults in this unit. These defects mainly consist of excessive gear run-out and gear teeth damage. In the present case, these faults were found to be the reasons for the doubling error in the tested press.

A new method for quantifying run-out is presented in the next section, utilizing techniques developed by the present authors in Ref. [2] for identifying gear tooth damage. They include wavelet amplitude analysis and beta kurtosis. In addition to gear damage detection, kurtosis is also shown in this work to provide another technique for identifying gear run-out.

5. Gear run-out detection using signal envelope

In this section, a new method for measuring gear run-out is developed. It will be applied to the diagnosis of the gear system in unit 2. Fig. 5(a) shows an example of a part of the MP signal, $V(t)$, from gear G7 in unit 2. Taking the Hilbert transform, the analytic signal V_a is obtained from

$$V_a(t) = V(t) + j \cdot V(t). \tag{4}$$

The envelope of V_a is then obtained as

$$V_e(t) = |V_a(t)|. \tag{5}$$

In order to check the signature more steadily, $V_e(t)$ is further low-pass filtered (Butterworth filter) with the cut-off frequency of five shaft orders, i.e., $5n/60$ Hz. The resulting envelope is shown in

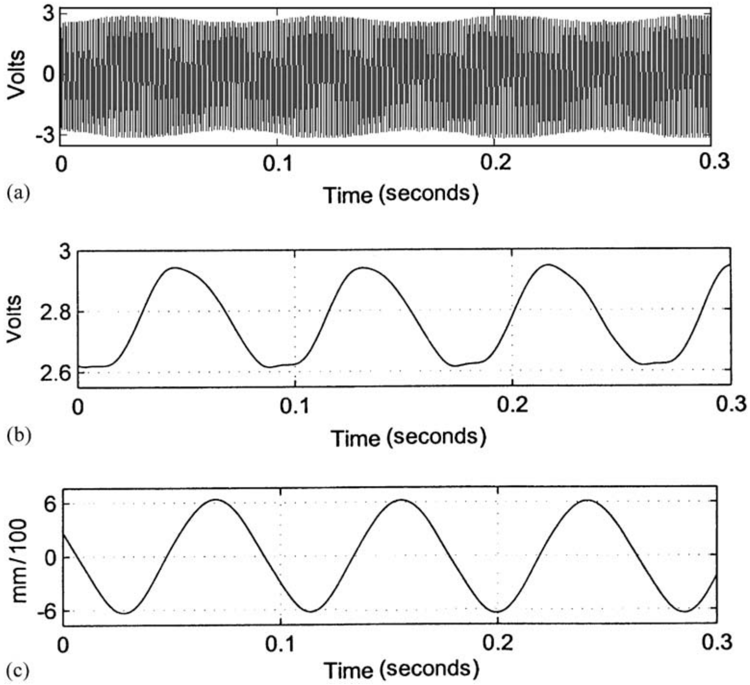


Fig. 5. (a) Part of MP signal; (b) envelope; (c) gear run-out.

Table 1
Comparison of the computed and measured gear run-out values

Gear no.	G1	G2	G3	G4	G5	G6	G7	G8
Calculated value (mm/100)	5.34	9.81	6.51	5.98	6.97	6.72	18.22	12.61
Measured value (mm/100)	4.98	10.37	6.73	5.52	6.61	7.38	19.17	13.08

Fig. 5(b). Since $V_e(t)$ is a speed related signal, the run-out is obtained from

$$R(t) = C_c \int_0^t V_e(t)\,\mathrm{d}t = C_c \int_0^t |V(t) + jV(t)|\,\mathrm{d}t, \tag{6}$$

where C_c is a calibration, and $C_c = 6.491 \times 10^{-2}\,\mathrm{mm\,V^{-1}}$ in this case. The MP calibration is conducted on a test apparatus that provides accurate gear run-out measurements (in mm), based on the amplitude value of the MP signal envelope in V (Volts) under different gear rotation speeds (in m/s).

Solving Eq. (6) numerically, the gear run-out signature is determined and shown in Fig. 5(c), which is 0.126 mm (peak-to-peak) in this case. Table 1 lists the calculated run-out values of the gears in unit 2 using the quantitative method in this section, along with dial indicator measurements conducted at a much lower speed for the purpose of verification. From the comparison, it is clear that the proposed method can be used effectively, online, to determine the gear run-out. From this table, it can be seen that run-out values of gears G2, G7 and G8 are larger than 0.080 mm (0.003 in), which is the tolerance for the gear systems in this press. Through inspection, it is found that the problems in gears G7 and G8 to be caused by large plays in the tapered roller bearings due to excessive wear, whereas the defect associated with G2 is caused by bearing damage.

It will be shown in the next section that the excessive gear run-out can also be identified from tooth-based beta kurtosis. The beta kurtosis, together with wavelet transform, will be utilized for detecting gear teeth damage.

6. Gear tooth damage detection

There are many vibration-based diagnostic techniques currently available in the literature for gear health condition monitoring, but each has its merits and limitations. According to our comprehensive assessment in Ref. [2], the most robust techniques include the beta kurtosis, the continuous wavelet transform, and the phase demodulation. In order to provide a more positive assessment of a gear's health condition, several of the robust fault diagnostic techniques should be utilized. In this work, the gear health condition is diagnosed by the use of the tooth-based beta kurtosis (BK) and continuous wavelet amplitude analysis (WT), employing the signal average and the overall residual signal. In this section, a brief description of the data processing techniques is given first. Results of applying these techniques for the fault diagnosis of the gears in unit 2 are then presented.

The first step for the health condition monitoring of a gear is to differentiate its specific signature from the collected MP signals. This process is conducted by using the time synchronous average (TSA) process [3]. TSA is taken over many records to reduce the noise not synchronous with the rotation of the gear of interest. The collected data size is determined by both noise attenuation requirements [4] and the computer memory limitations. Since an MP signal is a tooth-related signature, one tooth is chosen as the first tooth of the gear, and zero-crossing position in that tooth which is determined in Section 4 is selected as the start position of a revolution. For a collected signal, the number of samples per gear revolution may not be exactly equal from one revolution to another due to shaft speed variation. This fluctuation will affect the TSA adversely. To overcome this problem, a cubic interpolation [3] is applied to resample the obtained data set in each revolution. In this way, the same sample spans in each revolution could be guaranteed.

The overall residual signal is obtained by band-stop filtering out the gear meshing frequency and its harmonics. Since the collected gear signal $x(t)$ is periodic, the overall residual can be simply obtained in the frequency domain by a straightforward filtering process. As an example, for a gear with N teeth and the rotation speed of n rpm, the meshing frequency and its harmonics are $kNn/60$ Hz, $k = 1, 2, 3, \ldots$. If $X(f)$ is the FFT of $x(t)$, set $X(f)$ to zeros at $kN + 1$, $k = 1, 2, 3, \ldots$, the overall residual signal is then computed by the inverse Fourier transform process

$$x(t) = \text{real}[F^{-1}(2X(f))], \tag{7}$$

where the factor 2 appears because only a one-sided spectrum is used here.

Beta kurtosis, BK, is the fourth moment of the beta function. The application of the tooth-based BK to gear fault diagnostics is discussed in Ref. [5]. More detail about beta functions can be

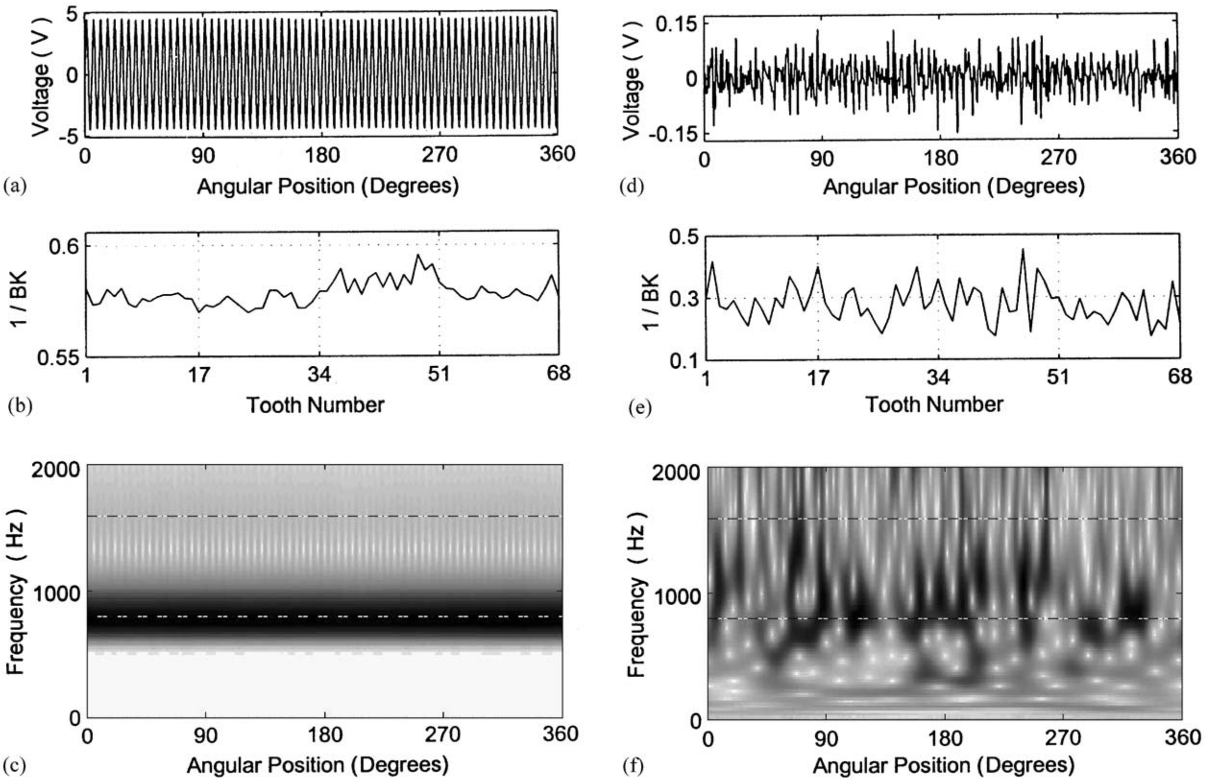


Fig. 6. Vibration of a healthy gear: (a, b, c) processed based on the signal average; (d, e, f) processed based on the overall residual signal. (a) Signal average, (b, e) beta kurtosis, (c, f) wavelet amplitude map, (d) overall residual signal.

seen in Refs. [6,7]. The wavelet transform, WT, is to represent a signal in the time–frequency domain. Morlet wavelet is chosen here as the mother wavelet in this study. The details of implementing the continuous wavelet amplitude to gear health condition monitoring can be found in Refs. [2,8].

The tests are conducted using the typical press operation conditions, i.e., with the same printing cylinder pressure and the cylinder speed of 700 rpm. Based on the MP data, the following are two typical test results for healthy and damaged gears in unit 2. Fig. 6 shows the results for a healthy gear, G6, in this unit. The signal average over 96 records (Fig. 6(a)) shows clear 68 peaks corresponding to 68 teeth of this gear. There is little fluctuation in the signature of BK in Fig. 6(b) due to small tooth surface imperfections. In the wavelet amplitude map in Fig. 6(c), the dashed lines denote the gear meshing frequency, MF, and its harmonics; it can be seen that the energy is mainly centred on the MF of 793 Hz. After band-stop filtering out the gear MF and its harmonics, more fluctuations appear in the trace of overall residual (Fig. 6(d)) and kurtosis signature (Fig. 6(e)) due to tooth surface imperfections caused possibly by wear, eccentricity, elastic deformation, etc. In Fig. 6(f), the distributed energy between the MF and its second harmonic is fairly uniform and thus does not indicate any abnormality in this case.

Fig. 7 shows the results for gear G7 at the same operating conditions. From the signal average trace in Fig. 7(a), there is no specific irregular signature except the apparent envelope fluctuations

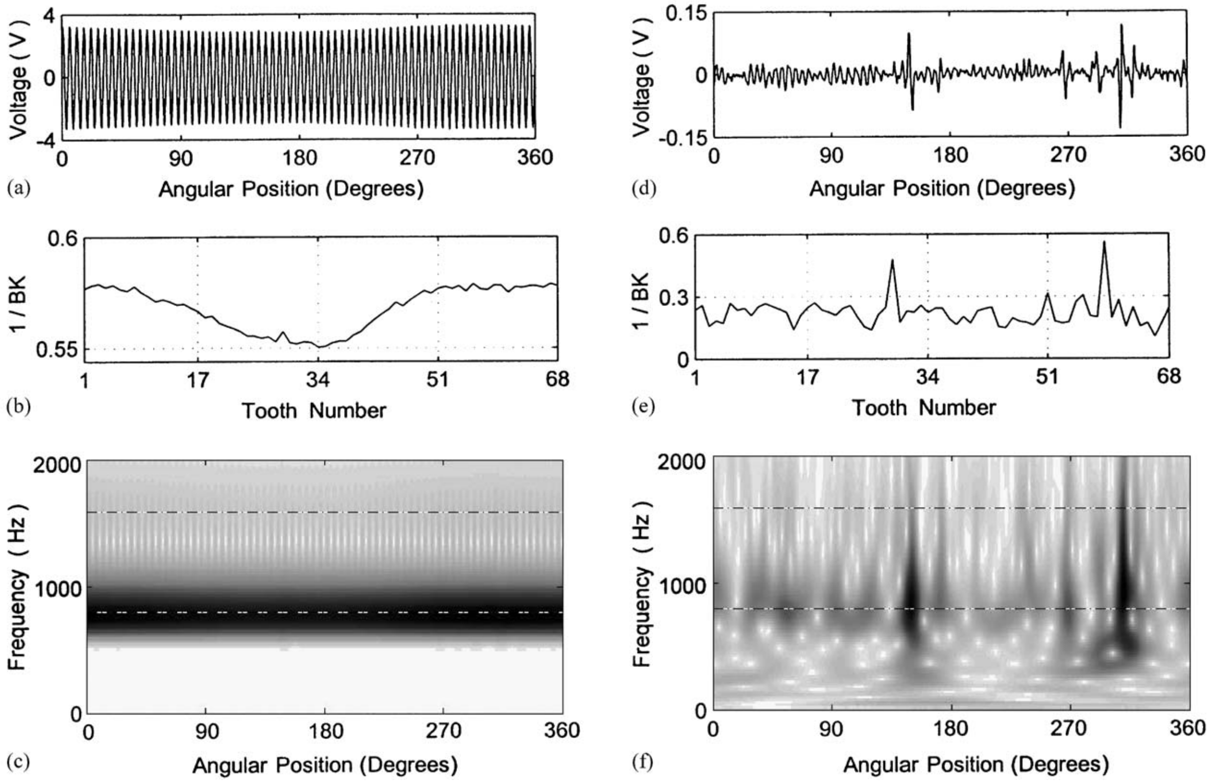
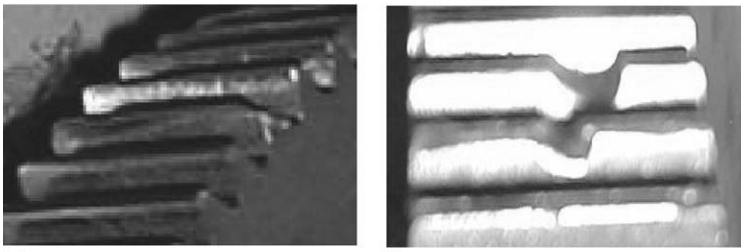


Fig. 7. Vibration of a damaged gear: (a, b, c) processed based on the signal average; (d, e, f) processed based on the overall residual signal. (a) Signal average, (b, e) beta kurtosis, (c, f) wavelet amplitude map, (d) overall residual signal.

due to an excessive gear run-out (0.182 mm). This run-out can also be picked up from the kurtosis signature in Fig. 7(b), indicating that tooth-based BK is very sensitive to the signal modulation. The wavelet amplitude map in Fig. 7(c) reveals that the energy is still centered around the MF. Compared to the overall residual signal in Fig. 7(d), the signature in Fig. 6(d) shows more (general) fluctuation, which may be caused by the higher noise level existing in the processing bandwidth. However, Fig. 6(d) does not reveal any irregular pattern because the signature is fairly uniform. But the overall residual signal trace in Fig. 7d clearly indicates that tooth damage exists around 150° and 320°. Moreover, these signature irregularities can also be identified from BK (Fig. 7(e)) around teeth 28 and 59, which are confirmed by the WT amplitude map in Fig. 7(f). The above diagnostic result has been verified through visual inspection, as shown in Fig. 8. The detected tooth faults are mainly caused by serious scoring damage (Fig. 8(a)) and the local tooth breakage (Fig. 8(b)).

Repeating the aforementioned diagnostic processes by positioning MPs to other gears, it was found that gear G2 in unit 2 also had tooth faults.

In summary, the doubling problem in this old press is due to transmission inaccuracies in unit 2, which are caused by excessive run-out in gears G2, G7 and G8, as well as by gear tooth damage in G2 and G7. It should be stated that the above problems are related to the unit with the highest



(a) (b)

Fig. 8. (a) Serious scoring tooth fault; (b) localized tooth breakage.

synchronization error level. The above techniques would also be applied to other units with lower synchronization errors that still violate the tolerance requirements.

7. Conclusions

This paper presented simple, yet effective techniques to identify sources of the doubling errors in multistage printing presses. The techniques were applied to a typical press. An algorithm for speed synchronization among stages (units) was implemented, and shown to isolate the unit responsible for the doubling correctly. In that unit, it was determined, using a new method. Based on the signal envelope, that run-out of some of the gears was out of tolerance. Also, using the known techniques of wavelet transform and beta kurtosis, teeth damage in some of the gears in the same unit was detected successfully. It is believed that the developed techniques could be implemented on a printing press not only to shorten the time of repair, but also to forecast the doubling problem on working presses ahead of time. More tests are currently conducted to apply the proposed techniques to other machines where the rotation synchronization on different stages is required.

Acknowledgements

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