Press Tonnage Signal Decomposition and Validation Analysis for Transfer or Progressive Die Processes

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A transfer or progressive die process consists of multiple stations working simultaneously in each stroke. This paper aims to develop a new methodology that can decompose press tonnage signals to obtain individual station signals without using in-die sensors. In the paper, two different tonnage decomposition tests, as well as the associated data analysis algorithms, are developed. Statistical profile analyses and an in-die sensor test were conducted to validate the proposed methodology.
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1 Introduction

In the last decade, transfer or progressive die processes have been widely used in stamping industry due to their high precision and high throughput performance. Because a transfer or progressive die process consists of multiple die stations, the press tonnage signals measured from the press linkages/columns are contributed by all individual stations. Therefore, it is not feasible to directly use the press tonnage signal to monitor each station condition. Although in-die sensors may be used to measure the individual station force directly, the technique still has limited applications in practice due to the extra cost and low reliability of sensors.

This paper aims to develop an innovative technique that decomposes the press tonnage signal to obtain individual tonnage signals generated from each station. In this paper, Sec. 2 provides an overview of transfer or progressive die processes and press tonnage signal measurements. In Sec. 3, two different tests and analysis procedures are presented to perform press tonnage signal decomposition. Statistical validation analyses are then discussed in Sec. 4 to check the consistency of the two test results. A real example is provided in Sec. 5 to demonstrate the effectiveness of the proposed methodology. Finally, the paper is concluded in Sec. 6.

2 Review of Transfer/Progressive Die Processes and Press Tonnage Signal Measurements

A transfer or progressive die process performs multiple operations by means of a die having several stations, each of which performs a different operation as the stock passes through the die. The difference between a transfer die process and a progressive die process is that they use different ways to move workpieces from one station to the next station. In a transfer die process, the sheet metal blank is cut from the coil before or at the beginning of the operations. Mechanical transfer devices are then used to move the individual workpieces from one station to the next station. Thus, a transfer die process can load workpieces separately at each station. However, in a progressive die process, intermediate workpieces are usually made from a continuous coil stock and are connected by a carrier strip until the final cutoff operation. Thus, a progressive die process cannot load workpieces separately into the die. The detailed comparison between a transfer die process and a progressive die process can be found in Ref. [1].

Figure 1 shows an example of a transfer die process that has six stations to produce a doorknob part. The measurement of the press tonnage signal is performed by the tonnage sensors (e.g., strain gage sensors) installed on the press linkages as shown in Fig. 1 [2]. The jaggedness of the tonnage signal is mainly due to the dynamic response of the die impulse force applied in the cutoff station and blanking station, which will be validated by the decomposed signals in Fig. 4. This doorknob process will be used as an example throughout the paper to illustrate the tonnage decomposition technique.

It should be clarified that, we used the term "transfer die process" in this paper to represent multiple operations occurred in a single press frame, which is different from the term of "transfer press line." A transfer press line usually has several single/independent presses, each of which has the capability to obtain force measures for a single operation by using press sensors. Thus, there is no need to do the tonnage decomposition for individual station condition monitoring in a transfer line.

3 Test and Analysis Procedures for Press Tonnage Signal Decomposition

During each press stroke, all stations work simultaneously and each station performs a different operation. When the process is fully loaded (i.e., all stations have workpieces loaded), the press tonnage signal is the summation of the forces generated at each station. Thus, the total stamping force F is

$$F = F_0 + \sum_{i=1}^{n} F_i \tag{1}$$

where F_0 is the initial die cushion force, F_i is the individual die stamping force at station i $(i=1,\ldots,n)$, and n is the total number of working stations in a multiple operation process. To monitor the condition of each working station, it is required to know the signal profile of the stamping force at each station. In this paper, a new methodology is developed to obtain each station force F_i based on press tonnage signal measurements. Two types of tests are proposed for press tonnage signal decomposition in a transfer die process, which will be presented in Secs. 3.1 and 3.2, respectively.

3.1 Single Station Test and Data Analysis. The procedures of the single station test are shown in Fig. 2. In this test, except for Step 0 of an empty hit (without any workpiece loaded in the die), only one station is loaded with one workpiece at each step. The same workpiece is moved from the first station to the last station sequentially during the test. Thus, this test is named as "single station test."

For a transfer die process with n working stations, the total number of test steps is equal to $n+1$. At Step 0 of an empty hit, the press tonnage measurement $f(0)$ is only contributed by the die cushion force F_0 as

$$f(0) = F_0 \tag{2}$$

At the following Step i $(i=1,\ldots,n)$, the press tonnage measurement $f(i)$ represents the force at the corresponding working station plus the die cushion force, that is,

$$f(i) = F_i + F_0, \quad i=1,\ldots,n \tag{3}$$

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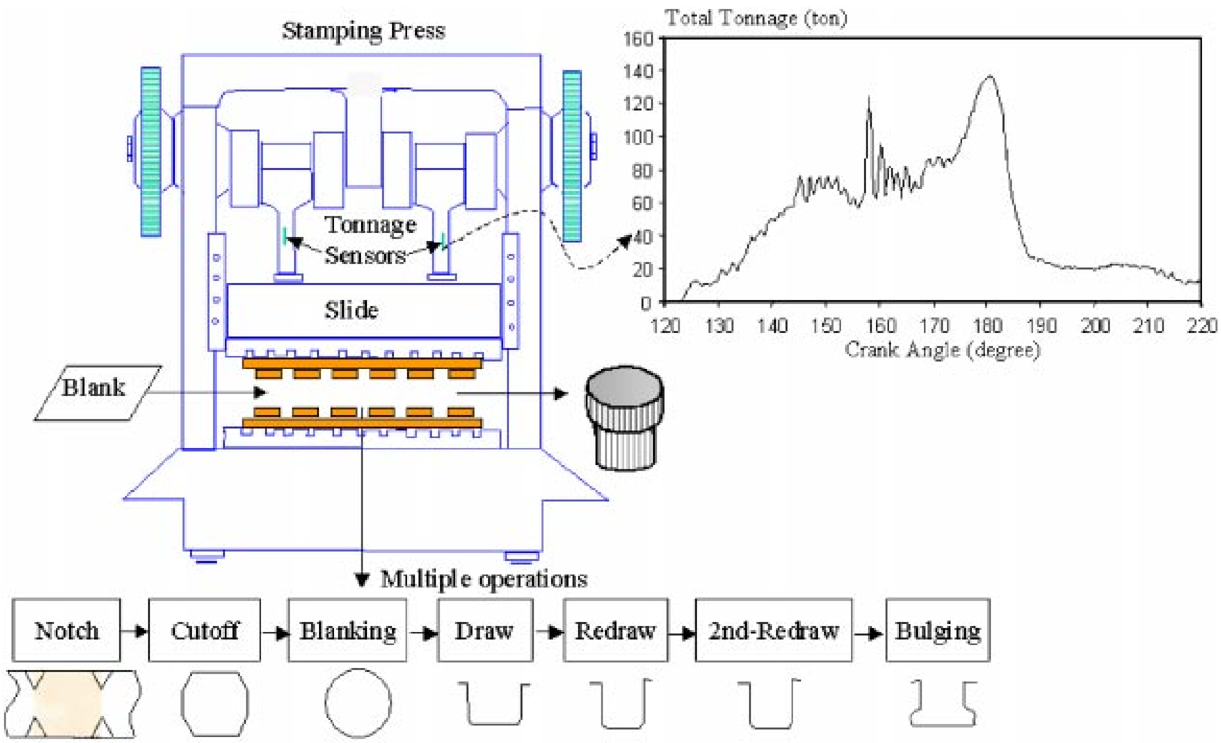

Fig. 1 Doorknob transfer die process

Based on this single station test, the decomposed individual force F_i at each station is

$$F_i = f(i) - f(0), \quad i = 1, \ldots, n \tag{4}$$

From Eq. (4), it can be seen that the decomposed tonnage signals F_i $(i=1,\ldots,n)$ are closely related to $f(0)$. Therefore, the empty hit needs to be conducted at each die setup if there is a change in the cushion parameters.

3.2 Feed-In and Feed-Out Test and Data Analysis. In the "feed-in and feed-out test" as shown in Fig. 3, except for Step 0 (i.e., the empty hit), all other steps are further divided into two test stages: the feed-in stage and the feed-out stage. At the feed-in stage from Step 1 to Step n in Fig. 3, a new workpiece is fed into the first station at each step, and the other existing loaded workpieces are moved sequentially from one station to the next station until the process is fully loaded. At the feed-out stage from Step $n+1$ to Step $2n-1$ in Fig. 3, one final stamping product is produced at each step by the last station, and the other existing loaded workpieces are moved forward sequentially from one station to the next station. Different from the feed-in stage, there is no new workpiece that is fed into the first station during the feed-out stage. This feed-out stage is finished when all workpieces are moved out from all stations. Considering both test stages of the feed-in stage and the feed-out stage, the whole test from Step 0 to Step $2n-1$ is called "feed-in and feed-out test," which consists of n test workpieces and $2n$ test steps conducted in n working stations.

In the feed-in and feed-out test, the press tonnage measurement $f(i)$ equals the total force of all loaded stations plus the die cushion force; that is,

$$f(i) = \begin{cases} \sum_{j=0}^{i} F_j, & (0 \leq i \leq n) \\ f(n) - \sum_{j=1}^{i-n} F_j, & (n+1 \leq i \leq 2n-1) \end{cases} \tag{5}$$

where $f(n)$ is equivalent to the total stamping force F when the process is fully loaded. Thus, the decomposed individual force F_j

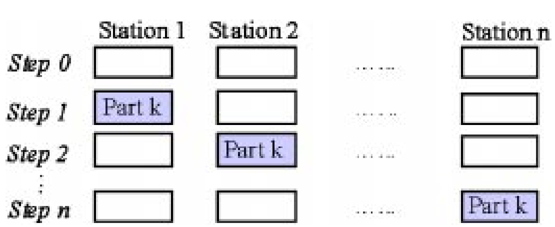

Fig. 2 The test procedure of single station test

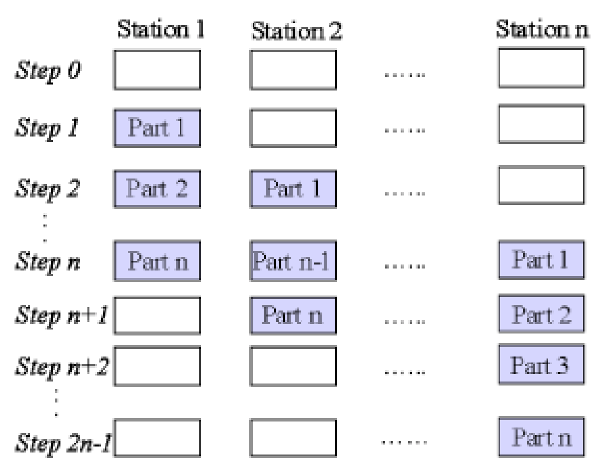

Fig. 3 The test procedure of the feed-in and feed-out test

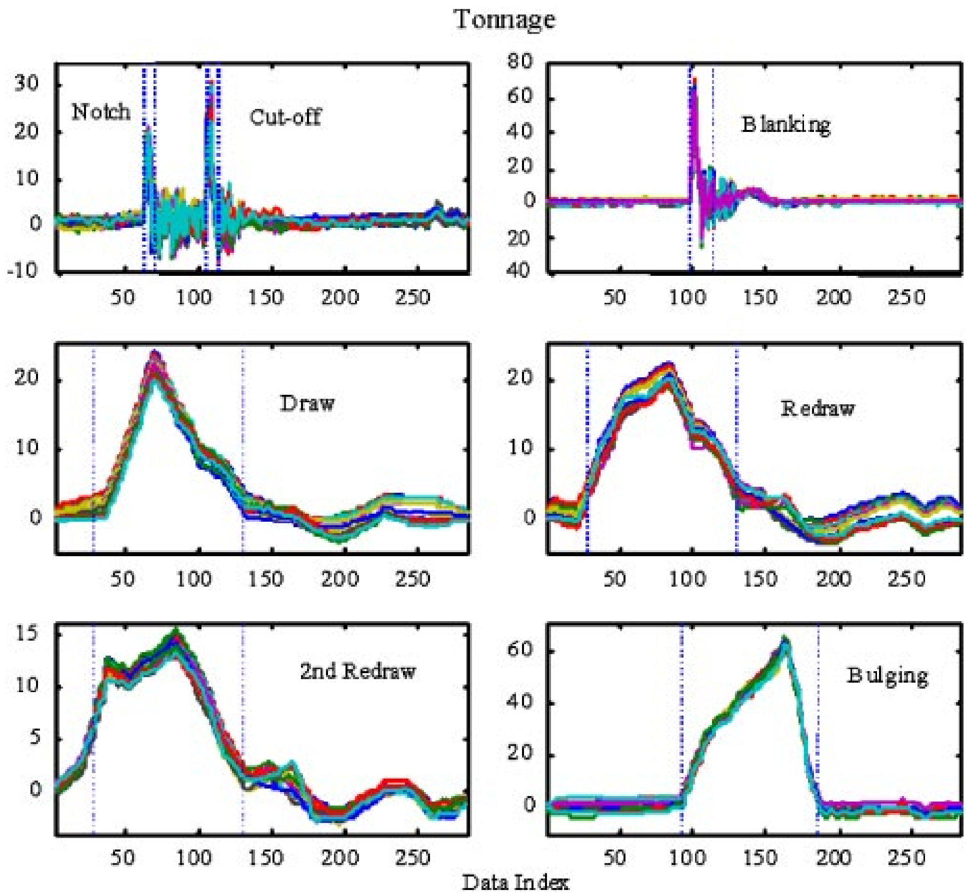

Fig. 4 Decomposed tonnage signals at each station under different tests

at station j can be calculated from either the feed-in stage (Step 1, . . . , Step n) or the feed-out stage (Step $n+1$, . . . , Step $2n-1$):

$$F_j=\begin{cases} f(j)-f(j-1), & \text{at the feed-in stage} \\ f(j+n-1)-f(j+n), & \text{at the feed-out stage} \end{cases} \tag{6}$$

where $1 \leqslant j \leqslant n$, and $f(2n)$ is equal to $f(0)$ of the empty hit.

Remarks. For a progressive die process, it is not feasible to conduct the single station test and the feed-out stage test because a carrier strip is always needed to move workpieces forward among stations. Thus, only the feed-in stage test can be conducted in a progressive die process. If the consistency of the decomposed signals under these tests is proven, then only one of these tests is needed in real applications. The statistical profile analysis will be discussed in the next section to check the consistency of these test results.

4 Statistical Profile Analysis for Waveform Signal Comparison

In order to validate the consistency of the decomposed signals between the feed-in and feed-out test and the single station test, a statistical profile analysis is used to check the consistency of the mean profiles under these tests.

Each cycle of tonnage signals corresponds to a complete stroke of a stamping operation to produce one stamping part. One cycle of tonnage waveform signals can be represented by p-correlated random variables,

$$x_i=[x_{i1},x_{i2}, \ldots ,x_{ip}]^{\mathrm{T}} \tag{7}$$

where x_{ij} represents measurement point j ($j=1, \ldots ,p$) of cycle i. It is assumed that different cycle signals are independent and follow a p-dimensional multivariate normal distribution $N(\mu,\Sigma)$, where μ is the mean of vector x_i, and Σ is the covariance matrix. The following two-step hypothesis testing is conducted for the corresponding two mean vectors [3]:

$$\begin{aligned} &\text{Step I:} \quad H_{I0}: \quad \mu_{i,j}-\mu_{i,j-1}=\mu_{k,j}-\mu_{k,j-1} \\ &\qquad\qquad H_{I1}: \quad \mu_{i,j}-\mu_{i,j-1}\neq\mu_{k,j}-\mu_{k,j-1} \end{aligned} \tag{8}$$

$$\text{Step II:} \quad H_{II0}: \quad \mu_{i,1}+\mu_{i,2}+\cdots+\mu_{i,p}=\mu_{k,1}+\mu_{k,2}+\cdots+\mu_{k,p}$$

$$H_{II1}: \quad \mu_{i,1}+\mu_{i,2}+\cdots+\mu_{i,p}\neq\mu_{k,1}+\mu_{k,2}+\cdots+\mu_{k,p} \tag{9}$$

where $\mu_{i,j}$ and $\mu_{k,j}$ (i, $k=1$, 2, 3; $j=2,3, \ldots ,p$) correspond to the means of measurement point j obtained at different test i and test k. Step I hypothesis test is used to check whether the mean profiles obtained under the different test i and test k are parallel to each other, and Step II hypothesis test is used to test whether the mean profiles under two tests i and k are coincident to each other. The detailed statistical conditions for rejecting the null hypotheses (H_{I0}, H_{II0}) in these two-step hypothesis tests are given below:

At Step I, for a given α of Type I error probability, the condition for rejecting the null hypothesis H_{I0} [3] is

$$T^2=(\overline{x_i}-\overline{x_k})^T C^T[(1/n_i+1/n_k)C\Sigma C^T]^{-1}C(\overline{x_i}-\overline{x_k})>\eta_I \tag{10}$$

where n_i and n_k are the number of the test samples in each test i and test k, respectively, and the matrix C is defined by

Table 1 The working range division of each station

Operation	Working range: Data index	Working range: Crank angle (degree)
Notch	[64 70]	[145.1 147.2]
Cutoff	[106 113]	[159.9 162.3]
Blanking	[100 113]	[157.8 162.3]
Draw	[27 131]	[132.1 168.7]
Redraw	[27 131]	[132.1 168.7]
Second redraw	[27 131]	[132.1 168.7]
Bulging	[93 187]	[155.3 188.3]

$$C_{(p-1)\times p}=\begin{bmatrix} -1 & 1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & -1 & 1 \end{bmatrix} \tag{11}$$

and η_I is given by

$$\eta_{\mathrm{I}}=\frac{(n_i+n_k-2)(p-1)}{n_i+n_k-p}F_\alpha(p-1,n_i+n_k-p) \tag{12}$$

where $F_\alpha(p-1,n_i+n_k-p)$ is the F distribution with the Type I error α and the degrees of freedom $p-1$ and n_i+n_k-p.

At Step II, for a given α of Type I error probability, the condition of rejecting the null hypothesis $\mathrm{H}_{\mathrm{II}0}$ [3] is

$$T^2=\mathbf{1}^T(x_i-x_k)[(1/n_i+1/n_k)\mathbf{1}^T\Sigma\mathbf{1}]^{-1}\mathbf{1}^T(x_i-x_k)>\eta_{\mathrm{II}} \tag{13}$$

where

$$\mathbf{1}_{1\times p}=[1\ \ 1\ \ \cdots\ \ 1]^{\mathrm{T}} \tag{14}$$

and

$$\eta_{\mathrm{II}}=F_\alpha(1,n_i+n_k-2) \tag{15}$$

5 Validation Analysis of the Decomposed Signals in the Doorknob Process

5.1 Doorknob Process Description. A doorknob process shown in Fig. 1 is used as a real industry example to demonstrate the proposed test procedures and to validate the effectiveness of the press tonnage signal decomposition methodology. A transfer die process of six working stations is used in the production, in which the notch and cutoff station is used to make a notch shape on the square workpiece and then cut each square blank from a continuous coil. The square workpiece is then moved to the blanking station to get a circular workpiece. After that, the part shape is progressively formed by three draw stations (draw, redraw, and the second redraw) and finally extruded at the bulging station.

5.2 Decomposed Tonnage Signals and Working Range Determination for Each Station. To validate the tonnage decomposition tests and algorithms, six test samples are collected from each single station test and feed-in and feed-out test, respectively. Thus, three sets of the decomposed signals are obtained for each station based on Eqs. (4) and (6), as shown in Fig. 4. Based on the design principle of a transfer die process, each die works only within a certain range of crank angles called the working range. Therefore, the consistency analysis of the decomposed signals under different tests should be conducted within only the working range of each station, which are given in Table 1 and shown by the dashed lines in Fig. 4.

5.3 Validation Analysis Results. Based on two steps of the profile analysis discussed in Sec. 4, the consistency of the decomposed signals obtained from Eq. (4) and Eq. (6) are validated. The analysis results are given in Table 2 and Table 3 to compare the consistency of the feed-in stage test and the feed-out stage test with the single station test, respectively. In the analysis, P-values are provided to show the smallest level of significance that would lead to reject the null hypotheses at each step [3]. If the obtained P-value is larger than the given α of Type I error probability, it concludes that there is no evidence to reject the null hypothesis. In the paper, a larger P-value indicates more consistency of the decomposed tonnage signals under the different tests. The P-values in Tables 2 and 3 are obtained corresponding to each step of the hypothesis test as

$$\text{For Step I:}\quad F_P(p-1,n_i+n_k-p)=\frac{n_i+n_k-p}{(n_i+n_k-2)(p-1)}T^2 \tag{16}$$

$$\text{For Step II:}\quad F_P(1,n_i+n_k-2)=T^2 \tag{17}$$

where $n_i=n_k=6$ is used.

Table 2 and Table 3, show that the single station test and the feed-in and feed-out test can all be used for the press tonnage signal decomposition in the doorknob transfer die process under a given Type I error probability less than 0.057.

5.4 Validation of the Decomposed Tonnage Signal Using an In-Die Sensor. The above validation results indicate that all decomposed signals obtained from different tests are coincident. However, further efforts are needed to validate the consistency between the decomposed signals with the real force generated in the station. Thus, an in-die sensor is used to measure the stamping force directly in the bulging station. The comparison of the in-die sensor signal and the decomposed signal at the bulging station is shown in Fig. 5. It can be seen clearly that both signals are coincident to each other. Further statistical analysis of these two pro-

Table 2 Comparison of the decomposed signals between the feed-in stage test and the single station test

Operation		Notch	Cut-off	Blanking	Draw	Redraw	Second redraw	Bulging
Step I	T^2	4.79	5.74	22.34	49.92	11.97	37.72	39.52
	P-value	0.720	0.650	0.810	0.560	0.935	0.653	0.634
Step II	T^2	1.14	0.96	1.08	1.69	0.79	0.0066	4.69
	P-value	0.310	0.350	0.320	0.220	0.390	0.940	0.057

Table 3 Comparison of the decomposed signals between the feed-out stage and the single station test

Operation		Notch	Cut-off	Blanking	Draw	Redraw	Second redraw	Bulging
Step 1	T^2	6.03	7.44	37.04	13.48	10.27	11.01	38.47
	P-value	0.630	0.540	0.660	0.918	0.953	0.945	0.646
Step II	T^2	2.57	4.58	4.2	0.325	1.79×10^{-4}	4.13	0.898
	P-value	0.140	0.058	0.068	0.581	0.990	0.0697	0.366

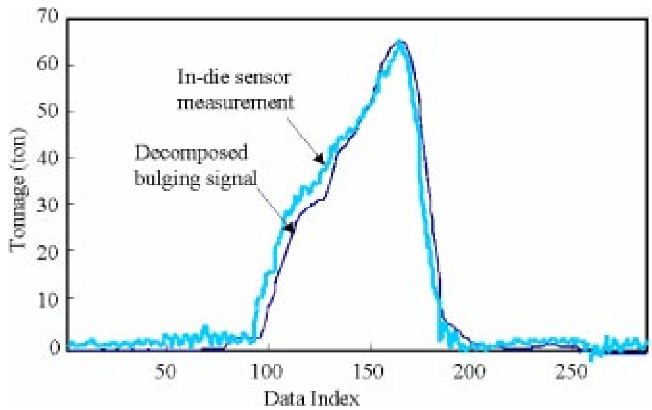

Fig. 5 Comparison of the in-die sensing and the decomposed signal at the bulging station

files also confirms above observation. This validation indicates that the decomposed individual signal is consistent with the in-die sensor measurement of the real stamping force.

6 Conclusions

This paper presents an innovative technique for press tonnage signal decomposition in transfer or progressive die processes. The validity of the proposed different tests has been evaluated by using the statistical profile analysis and the in-die sensor measurement. For a transfer die process, either the single test or the feed-in and feed-out test can be conducted, but for a progressive die process, only the feed-in test can be conducted. Fortunately, there is an advantage of using the feed-in test because it can be automatically conducted at the beginning of production after each coil change without additional efforts required. In this case, the variation of the feed-in test signals can also be utilized to analyze the run-to-run variation due to the coil change or different process setups.

It should be clarified that the proposed decomposition test does not aim to real time obtain decomposed tonnage signals for each stations. The purpose of using the decomposition tests is to obtain the knowledge of the signal profile of each station force, which can be used to effectively determine the monitoring segment for online individual station monitoring using the press tonnage signal [4,5]. Moreover, the decomposition test can indicate whether an overlap of tonnage forces exists among stations, which is useful to justify the necessity of installing in-die sensors [2].

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