TONNAGE SIGNATURE ATTRIBUTE ANALYSIS FOR STAMPING PROCESS

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ABSTRACT

A fault in the stamping process occurs when there is a deviation from acceptable limits of the process. Faults are dependent on the configuration of the press as well as the design of the die sets. The fundamental waveform of the tonnage signature is therefore a function of these factors as well as the location of the strain gages. The fault diagnosis problem is further compounded by the number of process faults that could occur over one cycle of the press. A methodology to reduce the complexity of the fault diagnosis problem is to first partition the tonnage signature (over one press cycle) into smaller segments. This reduces the number of faults to be considered at one time. The next step is to identify a set of signal attributes for each data segment. These signal attributes provide a quantitative measure of the process faults and are also pattern recognition tools for fault isolation or classification.

INTRODUCTION

The sheet metal stamping process is a very complex manufacturing process which involves over forty process variables. Much study of the effects of forming tonnage, drawbead design and material properties on the quality and dimensional accuracy of the part has been done. However, there is not much documentation on tonnage signals as a process monitoring tool although forces generated by the outer blankholder and the inner punch are known to be highly sensitive to a number of process variables [Ahmetoglu *et al* (1993)]-[Doege and Somer(1987)], [Siekirt (1986)].

Although some effort has been made to use these tonnage signals as a non-invasive means of process monitoring [Koh *et al* (1995)]-[Martinez-Heath and Bortfeld (1987)], [Seem and Knussmann (1994)], only Koh has attempted to extend this approach to multiple fault diagnosis. This paper discusses a further attempt to relate the tonnage signal to the extent of process faults. Three important observations are made here: (1) each segment can be partitioned to coincide with a distinct phase of the press cycle, (2) a set of inherent process faults can be found for each phase of the process, (3) each fault, in turn, can be quantitatively defined by a set of features in the tonnage signature. These observations imply that the tonnage signature over one press cycle can be broken up into smaller segments without any loss of information if the boundaries are properly drawn. This technique reduces the complexity of the diagnostic algorithm and also provides a means for quantifying and identifying the type of process faults.

The information needed for partitioning the original data is obtained from three sources – the press load/motion curves, engineering knowledge (of the press and process), and statistical data relating to the age and condition of the press. The fault domain for each segment is determined by the design of the press and the type of stamping process. The signal features attributed to each type of fault are based on engineering knowledge of the process variables, and verified by the study of numerous production and experimental tonnage signatures.

Three different combinations of press and die sets were studied to develop the approach presented in this paper. They were: I. a double-action underdrive press with a con-

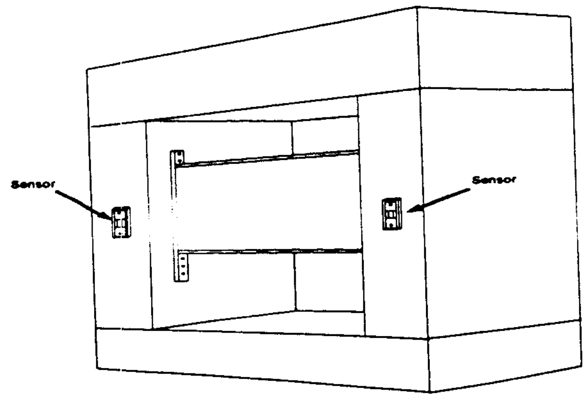

FIGURE 1: LOCATION OF SENSORS FOR OVERDRIVE STRAIGHT-SIDE PRESS.

ventional double-action die set, II. a triple-action overdrive press with a conventional double-action die set, and, III. a double-action overdrive press with a single-action stretch draw die. However, only the analysis for combination II (Fig. 1) will be presented in this paper to illustrate the methodology. Readers may refer to [Koh (1995)] for details on the other two press-die combinations.

FUNDAMENTAL TONNAGE WAVEFORM

The factors affecting the fundamental shape of the tonnage signature are discussed in this section.

Type of press

The type of press affects the tonnage signature through the transfer function between the point of force and the strain gage sensors. The high inertia of the press structure acts as a kind of low-pass filter and controls the frequency response of the strain gage transducers to a considerable degree. Different press structures produce different tonnage waveforms even if the same sensor systems are mounted at equivalent locations on these presses.

Sensor location and system

In an overdrive press, the four tie rods which hold the frame together are in tension while the four columns are in compression. Strain gauges may be mounted (by welding or bolting) on either the vertical columns or the links (or pitmans). In an underdrive press, the tie rods holding the frame together remain in compression but do not carry any press load during the cycle. Sensors in this case are mounted either on the top surface of the slides which undergo both tension and compression during the stroke, or on the connecting straps. Other factors include the frequency response of the strain gauges, possible sources of noise, cutoff frequency of the anti-aliasing filter, conversion rate and resolution of the analog/digital converter, and trigger signal, if any.

Design of die sets

Stretch draw and deep draw dies are quite different in construction and operation. Therefore, the shape of the basic tonnage waveform and types of faults are also different for different forming operations. Drawbead distribution and type of cushioning medium also vary from die to die.

SEGMENTATION OF TONNAGE SIGNAL

The tonnage signature over a complete press cycle can be partitioned into nearly disjoint segments representing distinct phases of the stamping process. A fault domain is associated with each segment, and each fault within a certain segment can be described by an inherent set of signal attributes or features.

When the crank angle rotates through 360° or one press cycle, the process undergoes several stages of dynamic interaction between the subsystems of the press, die and material. Different faults occur during each phase since different subsystems are interacting. These interactions are evident in the strong correlation of the shape and properties of these signals to the variables which influence this stage of the process [Siekirt (1986)], [Koh (1995)]. The boundaries of these segments can be determined using engineering knowledge of the press (motion and load curves), process knowledge (type of die set) and statistical properties of the data collected from production and experimental presses.

APPLICATION TO AN OVERDRIVE PRESS WITH CONVENTIONAL DRAW DIE.

Although the signals were taken from a triple-action Clearing (overdrive) press, it is very similar to that of a double-action with the exception of a dwell of approximately 1.5 seconds at bottom dead center (BDC). The tonnage signature over a cycle is partitioned into eight disjoint segments (Fig. 2). The set of signal attributes or features for the analysis of each segment are discussed in the following sections and summarized in Table 1.

Segment S_1 : 0° - 20°

The wear and condition of the clutch assembly can be monitored in this segment. The first (negative) peak T_{min} in Fig. 3 is due to the clutch engagement with the inner slide after the latter has been released by the brake. The inner slide is just off the top dead center (TDC) at the end of a cycle, although most manufacturers' motion curves will show it at TDC. The effort needed to pull it over the TDC exerts a reactive load on the crown which in turn compresses the columns. The second (positive) peak T_{max} is due to the downward thrust of the drive mechanism on the two slides after the latter have passed over the TDC. This action is translated into an upward force on the crown that puts the columns into tension. The condition of the clutch are indicated by the magnitudes of T_{min} and T_{max}. Poor clutch engagement due to wear produce higher variance in

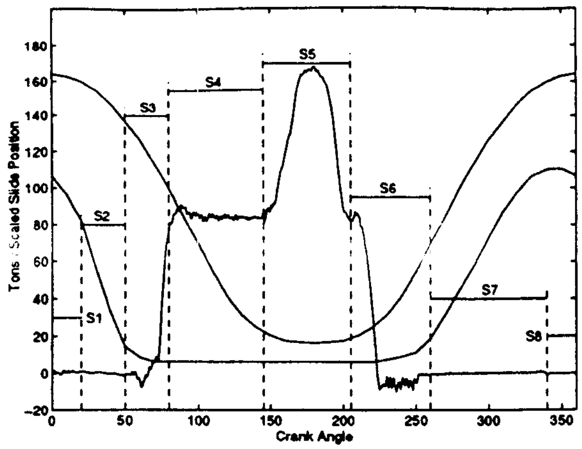

FIGURE 2: TONNAGE SIGNATURE AND MOTION CURVES.

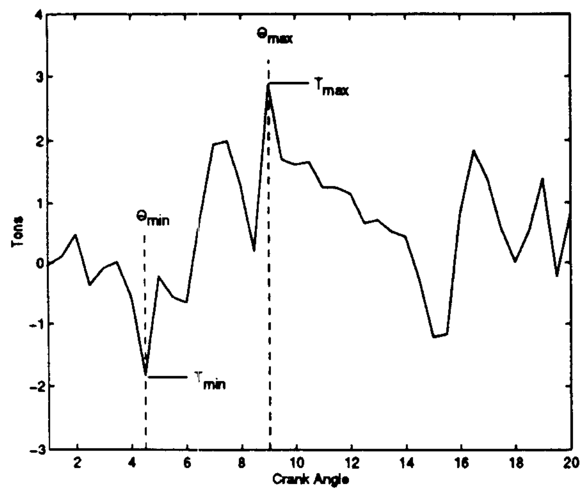

FIGURE 3: SIGNAL FEATURES IN SEGMENT S_1.

the tonnage readings in this segment. The "distance" between T_{max} and T_{min} measures the time taken for the clutch to fully engage the inner slide and bring it over the top. The clearances of the gibs at the top of the stroke are measured by the value of T_{max} at each corner. Gib bind will cause T_{max} to rise.

Segment S_2 : 20° - 50°

When the high frequency process noise has been removed from the signal, there is sometimes a dominant low frequency component (ω_o) over part or all of this segment. This oscillatory effect arises from a number of possible causes: (a) gib chatter due to wear, misalignment or excessive clearance, (b) gear noise, or (c) leakage in the counterbalance (C/B) seals. When this frequency, ω_o, is constant throughout and somewhat proportional to the rotational speed of a gear, it is known as gear noise. Gib chatter is usually localized and ω_o is observed only over parts

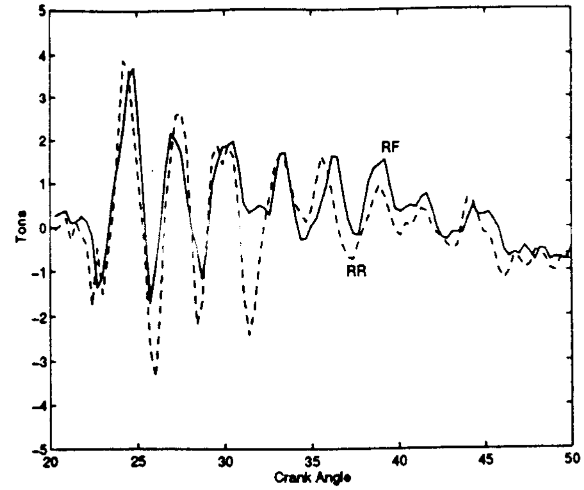

FIGURE 4: SIGNAL FEATURES IN SEGMENT S_2.

of this segment. Gib chatter due to excessive gib clearance often occurs in pairs. Two corners sharing the same crank shaft are in phase with each other but in almost opposite phase with the other two. Leakages in counterbalance seals produce irregular resistance against slide motion and the chatter is more erratic without any single dominant frequency throughout. The resulting motion is unpredictable as it depends on which seal is leaking - the inner slide has one counterbalance piston while the outer slide usually has two pistons. The chatter signal in this segment can be partially characterized by the following attributes:

1. $\delta\theta$: duration of the oscillations.
2. μ : mean value of the signal, $x(n)$, over the segment, that is,

$$\mu = \frac{1}{N_2}\sum_{n=1}^{N_2} x(n)$$

   where N_2 is the number of data points in segment S_2.
3. σ^2 : unbiased estimate of the variance of $x(n)$ over the segment.
4. ω_o : fundamental frequency of the oscillations.
5. ϕ : phase difference between signals from the same data segments of the four corners.

Figure 4 shows a typical signal in this segment.

Segment S_3 : 50° - 80°

This segment of the signature is indicative of the (a) deceleration of the outer slide, (b) nitrogen manifold pressure, and (c) gage size or blank thickness. Figure 5 shows some features of the signal in segment S_3.

When the outer slide approaches BDC, it is slowed down by a decelerating brake mechanism popularly referred to by its trade name Torc Pac. The inertia of the combined weight of slide and die tends to pull the crown

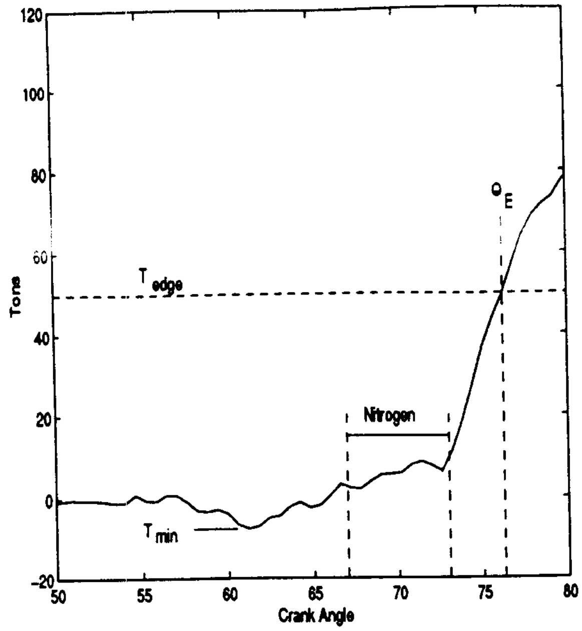

FIGURE 5: SIGNAL FEATURES IN SEGMENT S_3.

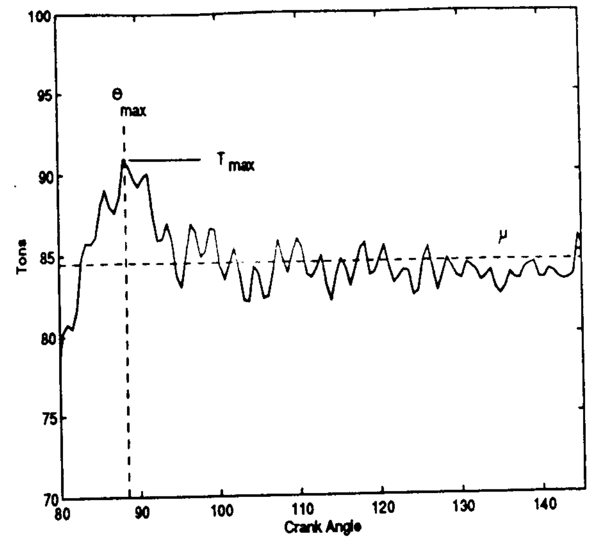

FIGURE 6: SIGNAL FEATURES IN SEGMENT S_4.

downwards and exerts a compressive force on the columns where the sensors are mounted. The amount of deceleration and hence the condition of the Torc Pac can be measured by (a) T_{min}, the lower T_{min} is, the more effective is the clutch system, (b) $\delta\theta_{T<0}$, the range of crank angle over which the tonnage, T, is negative, and (c) μ, the mean of the tonnage over $\delta\theta_{T<0}$. A negative threshold may be used in lieu of 0 if necessary.

The nitrogen cushion pressure can be monitored by the variance (σ^2) of the signal just before the rising edge. The gage thickness of the sheet metal can be estimated by tracking the edge (crank angle), θ_E, at which the tonnage crosses some prespecified level T_{edge}. A thicker blank means that the two dies will contact earlier in the cycle and hence a smaller value of θ_E is observed.

Segment S_4 : 80° - 145°

This segment offers an abundance of information about faults associated with the outer slide assembly. The most common of these are (a) loss of parallelism (due to any or a combination of the causes discussed in [Koh (1995)]), (b) thermal elongation of the links, (c) die wear, (d) gib clearance, (e) worn bushing, and (f) gage size. This segment represents one of two most important stages of the forming process.

Uneven ambient temperature around the press or operational heating (in the press and more commonly in the dies) can result in unequal reduction in the effective shutheights. This and other factors affect the parallelism of the outer slide assembly. Although it appears to be a trivial task to simply compare the four corner BHF, it is rare that all four corners have equal BHF due to part design. Die wear usually means a reduction in the height and width of the drawbeads. When this happens, the value of the maximum overshoot, T_{max}, is also reduced (Fig. 6).

The amount of (gib) clearance between the inner and outer slides determines the extent to which the following faults in the inner slide assembly are transmitted to the outer BHF signal: (a) misalignment between the two slides (due to loss of parallelism in either or both slides), (b) gear noise from the inner gear train, and (c) leakage in the inner counterbalance seal. The same analysis for segment S_2 may be applied to distinguish between the sources of the observed chatter - using the variance σ^2 and fundamental frequency ω_o. Worn bushings in the outer slide assembly may also create somewhat the same effect but this is hard to prove at this point.

Segment S_5 : 145° - 205°

This segment of the crank angle corresponds to the draw depth of the inner slide. It provides as much information about the drawing process as segment S_4 for the blankholding process. The following signal attributes are considered at this stage of the process:

1. T_P : peak tonnage.
2. θ_P : crank angle at T_P, typically, $\theta_P = 180°$.
3. W : duration of crank angle for which the drawing tonnage, $T \geq T_{ref}$, where T_{ref} is some prespecified level.
4. θ_E : crank angle at which T first reaches T_{edge}.
5. ω_o : fundamental frequency of the coining stage denoted by subsegment C.

A thicker gage size results in a higher T_P, a wider W (implying more energy required for forming) and an earlier

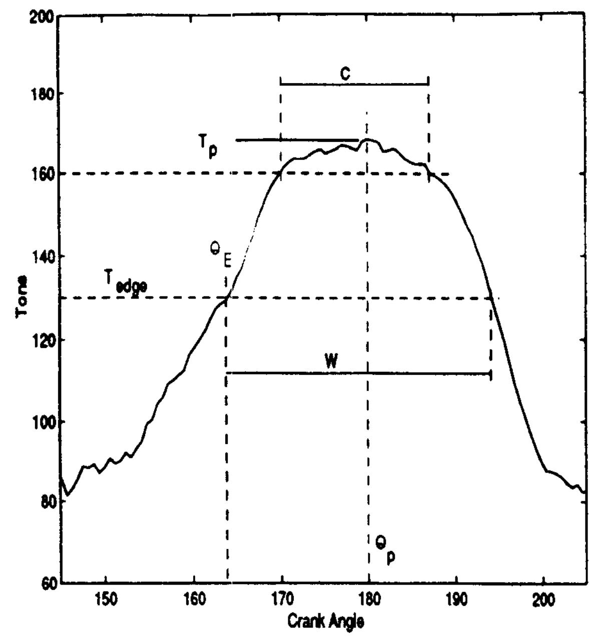

FIGURE 7: SIGNAL FEATURES IN SEGMENT S_5.

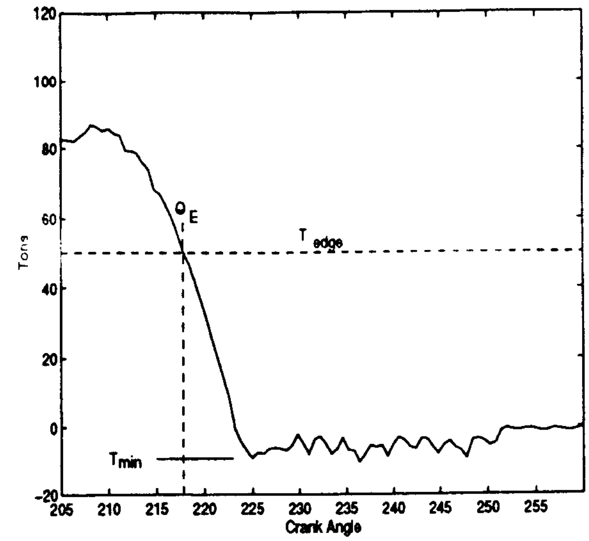

FIGURE 8: SIGNAL FEATURES IN SEGMENT S_6.

θ_E. A sudden reduction in W indicates either splits or a lower tensile strength of material. Parallelism of the inner slide is analyzed in the same way as in segment S_4, with the exceptions that (1) only the data in subsegment C are used to estimate μ_j, and (2) θ_P replaces θ_{max}.

A well-developed loose tie rod condition is easily detected by a significant drop in the value of T_P. Also, the maximum tonnage remains almost constant over a range of crank angle near the BDC. Since the strain gauges are mounted on the vertical uprights, the "plateau" will not disappear as T_P is increased, unlike the situation with link mounted strain gauges.

Segments S_6 and S_7 : 205°- 340°

The data in S_6 (Fig. 8) describes the accelerating capability of the Torc Pac clutch system and the nitrogen cylinder pressure. There have been claims that the tremendous pressure built up by the self-contained nitrogen cylinders during compression are released with such explosive effect during this time that dies are damaged. S_7 contains the same information as S_2.

Segments S_8 : 340° - 360°

Brake pad wear can be monitored in this segment. When the brake is new, it will catch the slide earlier in the cycle before it has fallen too far from TDC and acquired a higher velocity. When the brake is worn, it will engage the slide assembly later and more energy must be absorbed by the frame in the process. The positive peak, T_{max} in Fig. 9 is the point in the cycle when the slide is just before the TDC. At this instant, the inertia of the moving slide tends to push upwards against the crown and the strain gauges register a slight rise in tonnage. The negative peak, T_{min} corresponds to the point in the cycle when the brake engages the slide assembly and the kinetic energy of the moving slide assembly exerts a compressive force on the columns of the press through the brake assembly.

The magnitudes of T_{max} and T_{min} and the points on the cycle, θ_{max} and θ_{min} respectively, where they occur can be used to quantify the condition of the brake assembly.

CONCLUSION

Data collected from production and experimental presses have been combined with engineering knowledge of the press and process to formulate an approach to the diagnosis of stamping faults. The approach consists of: (a) partitioning the raw data into smaller segments to represent different phases of the process, (b) identifying a set of signal attributes to describe the faults for each segment, (c) relating the quantitative values of these attributes to the process dynamics. This pioneering work lay the foundation for a multiple fault detection and isolation scheme based on tonnage signatures [Koh (1995)].

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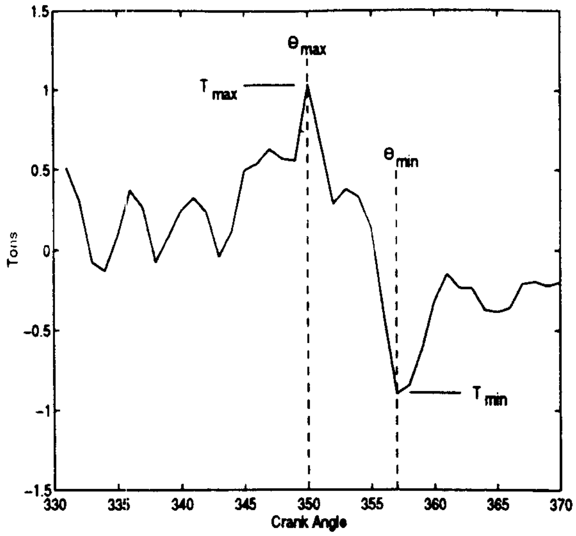

FIGURE 9: SIGNAL FEATURES IN SEGMENT S_8.

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Table 1: Summary of Signal Attributes

Segment and faults	Signal Attributes				
$S_1: 0° \sim 20°$	σ^2	T_{min}	θ_{min}	T_{max}	θ_{max}
F_1. Clutch wear	x	x	x	x	x
$S_2: 20° \sim 50°$	σ^2	μ	ω_o	ϕ	$\delta\theta$
F_1. Gib chatter	x	x	x	x	x
F_2. Gear noise	x	x	x	x	x
F_3. C/B seals	x	x	x	x	x
$S_3: 50° \sim 80°$	T_{min}	$\delta\theta_{T<0}$	μ	σ^2	θ_E
F_1. Torc Pac	x	x	x		
F_2. Nitrogen				x	
F_3. Gage size					x
$S_4: 80° \sim 145°$	T_{max}	θ_{max}	μ	σ^2	ω_o
F_1. Parallelism	x	x			
F_2. Thermal (BHF)	x		x		
F_3. Die wear	x				
F_4. Gib clearance				x	x
F_5. Bushing (outer)	x	x		x	x
F_6. Gage size	x		x		
$S_5: 145° \sim 205°$	T_P	θ_P	ω_o	θ_E	W
F_1. Gage size	x			x	x
F_2. Parallelism	x	x	x		
F_3. Thermal (ram)	x				
F_4. Tie Rod	x		x		
F_5. Bushing	x	x	x		
F_6. Yield stress	x				
$S_6: 205° \sim 260°$	T_{min}	$\delta\theta_{T<0}$	μ	σ^2	θ_E
F_1. Torc Pac	x	x	x		
F_2. Nitrogen				x	
F_3. Gage size					x
$S_7: 260° \sim 340°$	σ^2	μ	ω_o	ϕ	$\delta\theta$
F_1. Gib chatter	x	x	x	x	x
F_2. Gear noise	x	x	x	x	x
F_3. C/B seals	x	x	x	x	x
$S_8: 340° \sim 360°$	σ^2	T_{min}	θ_{min}	T_{max}	θ_{max}
F_1. Brake wear	x	x	x	x	x