# Industrial Lubrication and Tribology

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**Abstract**

**Purpose** – For oil film thickness measurement using ultrasonic spring model, obtaining the isolated reflection from the oil film layer is the key point. While for oil film thickness measurement in thrust bearings with thin liner, the reflection from the substrate-Babbitt interface will overlap with the reflection from the oil film layer. This overlapping will render the ultrasonic spring model invalid. To obtain the isolated reflected signal from the oil film layer accurately, an adaptive method was developed to recover the overlapping echoes.

**Design/methodology/approach** – A genetic-algorithm-based support matching pursuit (GA-based SMP) was developed to provide the optimal echo number and initial parameters guesses automatically and efficiently. Then, the traditional expectation maximization (EM) model was used to fine tune the accurate results.

**Findings** – The developed method was tested using both simulated echoes and the overlapping echoes encountered in the ultrasonic oil film thickness measurement of thrust bearings. The results demonstrated that the developed method performed well on recovering overlapping echoes adaptively.

**Originality/value** – The work shows an adaptive method to recover the ultrasonic overlapping echoes. When used in ultrasonic oil film thickness measurement, it can help extend the application of traditional ultrasonic spring model to objects with four or more layers.

**Keywords** Adaptive, EM method, GA-based SMP method, Overlapping echoes, Ultrasonic spring model

**Paper type** Research paper

## 1. Introduction

Ultrasonic spring model is an emerging and promising method for measuring oil film thickness below 10 $\mu$m (Dwyer-Joyce *et al.*, 2003; Zhang *et al.*, 2005). It uses the reflection ratio of the incident ultrasound on the oil layer to calculate the oil film thickness. In the oil film thickness measurement using the ultrasonic spring model, attaining the isolated echo reflected from the oil layer is the key point. Most objects measured in previous studies were modeled as three-layer (steel-oil-steel) structures (Hunter *et al.*, 2012; Mills *et al.*, 2013; Drinkwater *et al.*, 2009; Reddyhoff *et al.*, 2006; Dwyer-Joyce and Kasolang, 2006). The echo reflected from the oil layer is inherently isolated (Figure 1), so it is easy to obtain the reflection coefficient and then calculate the corresponding oil film thickness. For the oil film thickness measurement in some applications, such as thrust bearing, there is normally a Babbitt liner on the surface of the substrate. Therefore, the structure becomes a four-layer structure comprising the substrate-Babbitt-oil-steel composition. When the Babbitt liner is thin, the echo reflected from the substrate-Babbitt will overlap with the one reflected from the oil layer (Figure 2) (Drinkwater *et al.*, 2006; Zhang *et al.*, 2015). It is not possible to obtain the reflection coefficient because of the overlapped echo and then invalidation of the ultrasonic spring model occurs, as the echo reflected from the substrate-Babbitt interface will pollute the original frequency spectrum of the echo reflected from the oil film layers.

One way to overcome this problem is to extract the required echo from the overlapping echoes. In 2001, Demirli and Saniie (2001a, 2001b) etc., first proved that the wideband ultrasonic echo can be well modeled as a Gaussian echo and demonstrated that the expectation maximization (EM) method is effective in recovering overlapping echoes. In 2015, Zhang (Zhang *et al.*, 2015) applied the EM algorithm to obtain the required ultrasonic echo from the overlapping echoes encountered in the ultrasonic oil film thickness measurement of thrust bearings. They

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Industrial Lubrication and Tribology
69/5 (2017) 788–797
© Emerald Publishing Limited [ISSN 0036-8792]
[DOI 10.1108/ILT-01-2016-0011]

This work was funded by the National Science Foundation of China under grant No. 51705140 and 51675403.

Received 23 January 2016
Revised 5 May 2016
Accepted 7 March 2017

**Figure 1** Schematic of three-layer structure and the isolated echo reflected from the steel-lubricant layer

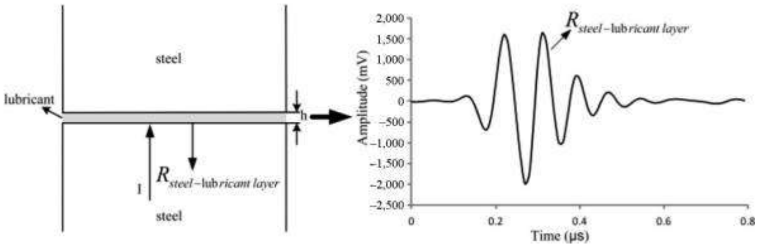
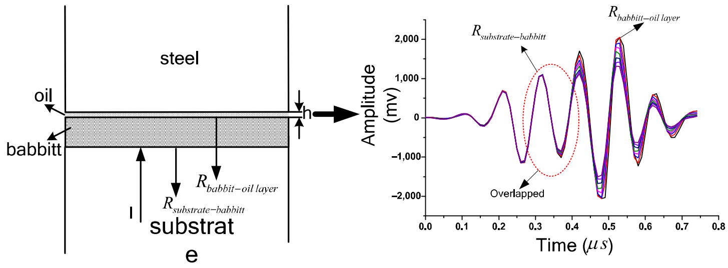


**Figure 2** Schematic of four-layer structure and the overlapped echoes





demonstrated that the EM algorithm can recover accurately the echo reflected from the oil layer and thus help to extend the application of ultrasonic spring model for oil film thickness measurement to structures of four or more layers.

However, when recovering the composed echoes from the overlapping echoes, the EM algorithm requires prior knowledge, that is, the exact number of the echoes in the superimposed signal and initial guesses close to the optimum to start. Furthermore, for the closely spaced overlapping echoes, the results of the EM method are very sensitive to the initial guess. The strong dependence of the results on the initial guess makes it is very necessary and significant to develop an adaptive method for the overlapping echoes recovery.

Among the adaptive decomposition methods, the methods based on the matching pursuit (MP) (Mallat and Zhan, 1993) have been extensively used for ultrasound signal processing because of their efficiency and ease of use (Lu and Michaels, 2008; Chul *et al.*, 2006). The most important shortcoming of the MP method is that it uses correlations to obtain best matching basic functions (atoms) which often yields basic functions matched to global signal while smearing out local signal components. In 2010, E. Mor (Mor *et al.*, 2010) proposed the support matching pursuit (SMP) to approximate the overlapping echoes and decompose each echo possessing physical meanings. Theoretically, as an adaptive method, the SMP is expected to recover the echoes accurately from the overlapping echoes, while it encounters the conflict between computational complexity and the precision of the results. The realization complexity is tremendously high when the dictionary is pre-defined to be large so as to obtain the high-accurate results.

Aiming to obtain an adaptive method with both low computation complexity and high precision results, two treatments were done to the above-mentioned methods. First, we developed the genetic-algorithm-based (GA-based) SMP to increase the computation speed and the practicability of the SMP. The SMP method selects the best matching basic function at each iteration from a large pre-defined dictionary, whereas the GA-based SMP uses the GA to optimize the dictionary and obtain the parameters of best matching basic function at each iteration from a dynamic optimization dictionary. Benefiting from good global search ability and small computation amount of GA for multiparameter solutions, the GA-based SMP can improve the computational efficiency and extend the searching space of the SMP. The other deal is that the GA-based SMP was used to provide the echo number and the initial guess for the EM method rather than obtain the final accurate results. The combination of the GA-based SMP method and the EM method can balance the computation complexity and the accuracy of the results and then is expected to be an adaptive method with both high efficiency and high precision.

The rest of the paper is organized as follows. In Section II, the EM method as well as the GA-based SMP method is introduced. Section III reports the performance of the presented method for simulated signals, where closely spaced overlapping echoes is tested for 1,000 times, the performance of the presented method is compared with both the traditional EM method and the method obtaining initial guess by SMP itself. The application of the proposed method for recovering the required echo from the overlapping echoes in ultrasonic oil film thickness measurement of four-layered structure is described in Section IV. Finally, conclusions are drawn in Section V.

## 2. Methodology

### 2.1 Gaussian echo model

It's well known that a wideband ultrasonic echo reflected from an interface can be modeled as Gaussian echo model (Demirli and Saniie, 2001a, 2001b):

$$s(\theta;t) = \beta e^{-\alpha(t-\tau)^2}\cos(2\pi f_c(t-\tau)+\phi) \qquad (1)$$

Where $\theta = [\alpha\ \tau\ f_c\ \phi\ \beta]$ denotes the parameter vector to be measured of a single echo.$\alpha$ is the bandwidth factor, $\tau$ is the arrival time, $f_c$ is the center frequency, $\phi$ is the phase and $\beta$ is the amplitude.

When each parameter in the vector $\theta$ varies in the range of $\pm 10$ per cent away from the actual value, the corresponding reconstruction error of the ultrasonic echo is shown in Figure 3. The reconstruction error is defined as:

$$E_r = 10\log_{10}\left(\frac{\|s_\theta(t) - s_{\hat{\theta}}(t)\|^2}{\|s_\theta(t)\|^2}\right)dB \quad (2)$$

Where $\hat{\theta}$ is the estimated parameter vector of a single echo.

From Figure 3, it can be seen that the most sensitive parameters for the reconstruction error of a single echo are identified in sequence as the arrival time $\tau$, the center frequency $f_c$, the amplitude, $\beta$ the phase $\phi$ and the bandwidth factor $\alpha$. On the other hand, when providing the initial guesses, the arrival time $\tau$ and the center frequency $f_c$ need to pay most attention. A poor initial guess on these two parameters may cause the failure of the estimations.

### 2.2 EM method

Expectation maximization is a well-known effective method for recovering overlapping echoes. It translates the multi echo estimation problem into isolated echo estimation problems. In the EM algorithm, the M-step uses the Gaussian Newton algorithm to estimate the parameters of the echoes. The steps of the EM method are listed below (Feder and Weinstein, 1988; Demirli and Saniie, 2001a).

*Step 1*: Determine the echo number $M$ and the initial guess near optimal values of each composed echo, construct the initial guess matrix $\Theta^{(0)} = [\theta_1^{(0)}; \theta_2^{(0)}; \ldots; \theta_M^{(0)}]$ and then set the interaction number as $k = 0$.

*Step 2*: For $i = 1, 2, \ldots M$ compute the expected echoes (E-Step):

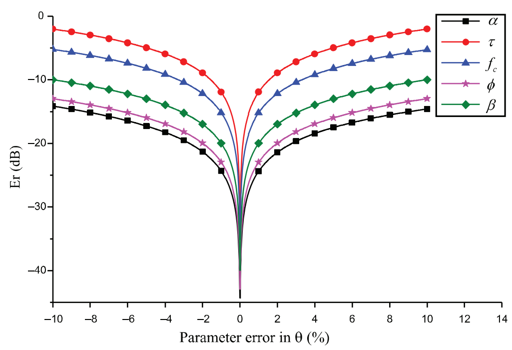
$$\hat{x}_m^{(k)} = s(\theta_m^{(k)}) + \frac{1}{M}\left\{f(t) - \sum_{i=1}^{M} s(\theta_m^{(k)})\right\}$$

*Step 3*: For $m = 1, 2, \ldots M$, iterate the corresponding parameter vector by the Gauss Newton algorithm (M-Step) (Demirli and Saniie, 2001a), giving:

$$\theta_m^{(k+1)} = \arg\min_{\theta_m} \|\hat{x}_m^{(k)} - s(\theta_m)\|^2$$

*Step 4*: Check convergence criterion: If $\|\Theta^{(k+1)} - \Theta^{(k)}\| \leq \varepsilon$ (where $\varepsilon$ is the tolerance), then stop this loop. Else, go to step 5.

**Figure 3** Error effects on reconstruction error for each parameter in $\theta$




*Step 5*: Set $k = k + 1$ and then go to Step 2.

Although EM method is an effective method for recovering overlapping echoes, it requires that prior knowledge of the echo number and good initial guesses near optimal values are available to start. Furthermore, for closely spaced overlapping echoes, the results of the EM are very sensitive to the initial guess. In this work, to balance the computer complexity and accuracy of the results, the GA-based SMP method was developed to provide echo number and initial guesses for the EM method.

### 2.3 Providing echo number and initial guess by GA-based SMP

#### *2.3.1 Principle of SMP*

The principle of SMP is the same as the MP (Mallat and Zhan, 1993; Lu and Michaels, 2008) except using a different optimal basic function selection criterion. It decomposes a complex signal into the linear superposition of the basic functions $h_n$ ($\|h_n\| = 1$) that are selected from a redundant basic function dictionary D:

$$f(t) = \sum_{n=1}^{M} a_n h_n(t) + r_{M+1}(t) \quad (3)$$

Where $M$ denotes the number of the basic functions into which a complex signal is decomposed, $r_{M+1}(t)$ denotes the final residue of the complex signal, $h_n(t)$ denotes the basic function selected from a redundant basic function dictionary D, $a_n$ denotes the corresponding expansion coefficient of $h_n(t)$ and it can be obtained by:

$$a_n = < r_n(t), h_n(t) > = \int_{-\infty}^{+\infty} r_n(t) h_n^*(t) dt \quad (4)$$

Where $h_n^*(t)$ is the complex conjugate function of $h_n(t)$.

Different from that the MP method selects the optimal basic function of each iteration merely in the light of the highest absolute correlation coefficient, the optimal basic function selection criterion of the SMP uses both the absolute correlation coefficient and the robust support of the resulting residue. This selection criterion in SMP has been proved to be more suitable for the decomposition of ultrasonic signal. In detail, at $n - th$ iteration, the SMP method first selects all the basic functions corresponding to an absolute correlation coefficient above a specific threshold $t_n$ (Mor *et al.*, 2010):

$$P_n = \{p: |a_n(p)| > t_n = (K\|r_n\|^2)/N\} \quad (5)$$

Where $a_n(p)$ is the $p - th$ element of the correlation coefficient vector at $n - th$ iteration, $r_n$ is the current residual signal at $n - th$ iteration, $N$ is the sample number, $K$ is a constant typically between $2 \leq K \leq 3$ (Tropp *et al.*, 2006), and is set to be 2.5 in this work (Mor *et al.*, 2010).

Then choose the basic function resulting in next residue with the lowest robust support from the set $P_n$ as the optimal basic function of $n - th$ iteration (Mor *et al.*, 2010):

$$\hat{p}_{optimum}(n) = \arg\min_{p} \left\{\sum_{i=1}^{N} |r_{p,n+1}(t_i)|^{\xi}\right\} \text{ for } 0 \leq \xi \leq 1 \quad (6)$$

Where $p_{optimum}(n)$ denotes the optimal basic function at $n - th$ iteration, $\xi$ is set to be 0.1, $r_{p,n+1}$ denotes the next residual signal of $n - th$ iteration for each basic function in $P_n$:

$$r_{p,n+1} = r_n - a_n(p)h_p \tag{7}$$

Where $h_p$ is the $p - th$ column of the basic function dictionary.

*2.3.2 GA-based SMP*

In the SMP method, the basic function dictionary is first constructed and then the optimal atoms are selected from the dictionary continuously. The normal method to form the basic function dictionary predefines all the possible solutions in the light of the precision requirements and the scope of the solution. The dictionary formed by this method is often very large and the realization complexity is tremendously high when finding the best basic function from the dictionary, especially aiming to obtain the high-accurate results.

In this work, to increase the computer speed and reduce the computer complexity of the SMP, we developed the GA-based SMP. We set only some possible solutions in the light of the scope of the solution, optimize the dictionary continuously and select the optimal atoms from the dynamic dictionary. Benefiting from good global search ability and small computation amount of GA for multiparameter solutions, the dictionary formed by this method is expected to obtain good results with low realization complexity.

In detail, Gauss echo model which is normalized to have unit energy was chosen here as the basic function model:

$$h_n(t) = k_n e^{-\alpha(t-\tau)^2}\cos(2\pi f_c(t - \tau) + \phi) \tag{8}$$

Where $k_n$ is the normalization coefficient to ensure each basic function with unit energy.

GA was adopted to optimize the dictionary and SMP was used to obtain the mostly optimal parameter solutions. The outline of the GA-based SMP was shown in Figure 4 and the steps of GA-based SMP are listed as follows:

*Step 1*: Initialize the iteration counter $n = 1$ and the residue $r_1 = f(t)$ where $f(t)$ is the received signal; set the analysis domain of the parameters $\alpha$, $\tau$, $f$ and $\phi$ of the basic function model; set the population size, maximum number of generations and the probability of selection, crossover, mutation in GA algorithm.

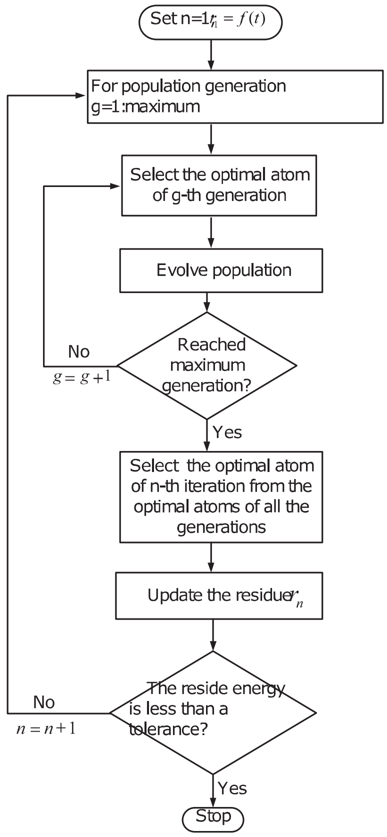
*Step 2*: Code the four parameters $\alpha$, $\tau$, $f$, $\phi$ of the basic function model and produce an initial population.

*Step 3*: For each chromosome, normalize the corresponding basic function represented; calculate the correlation coefficient between each normalized basic function and the residue $r_n(t)$ by equation (4).

*Step 4*: Select all basic functions whose absolute correlation coefficients with the current residue are above threshold $t_n$, according to equation (5), from the population; record them as the candidate set of the optimal basic functions of this generation.

*Step 5*: Choose the basic function resulting in the next residue with the lowest robust support from the candidate set, according to equation (6), as the optimal basic function of this generation.

**Figure 4** The outline of the GA-based SMP




*Step 6*: Do selection, crossover and mutation operations to obtain an evolved population.

*Step 7*: Repeat steps 3-6 until the evolution reaches the maximum number of preset generation.

*Step 8*: The optimal basic functions of all the generations form the optimal basic function candidate set of $n - th$ iteration; then select the basic function resulting in next residue with the lowest robust support from it; record it as the optimal basic function of $n - th$ iteration.

*Step 9*: Update the residue $r_n$ by subtracting the optimal basic function obtained at the $n - th$ iteration from the current residue.

*Step 10*: If the residue energy is less than a tolerance then stop. Otherwise, set $n = n$ 1 and then go to Step 2.

By conducting the above procedure, we can obtain the echo number and initial guess of each composed echo for EM method. Here, one needs to notice that there are only four parameters of the parameter vector $\theta$ and they were resolved by the GA-based SMP at each iteration, another parameter $\beta_n$ can be obtained by:

$$\beta_n = a_n \cdot k_n \tag{9}$$

Where $a_n$ is the correlation coefficient between the optimal basic function of each iteration and the current residue $r_n(t)$, $k_n$ is the normalization coefficient of the optimal basic function of each iteration.

## 3. Simulation

To test the performance of the proposed method for recovering overlapping echoes, a simulation example consisting of two closely spaced overlapping echoes in time with additive white Gaussian noise (WGN) was constructed:

$$f(t) = \sum_{i=1}^{2} s_i(\theta_i, t) + n(t) \quad (10)$$

Where $n(t)$ denotes the WGN, $\theta_i$ are the echo parameters, and

$$\theta_1 = [40, 0.5, 5.6, 0, 1.0] \quad (11)$$

$$\theta_2 = [36, 0.7, 4.3, 1.9, 0.8] \quad (12)$$

This superimposed echo is sampled at the sampling frequency $f_s = 100MHz$ and stored in a signal vector $f_0(t)$. A realization of a zero mean WGN sequence with variance $\sigma^2$ is added to the superimposed echo to form the simulated signal $f(t)$. Here, a variance of noise sequences is generated to simulate echoes with SNR of 15 dB. In the GA-based SMP process, the settings adopted in the GA are shown in Table I.

Gray code is used in coding the echo parameters, and the selection strategy is tournament selection. Multi-point crossover is used and the mutation is carried out such that randomly chosen four bits of the gene mutates according to the mutation probability. The algorithm stops when the population evolves 200 generations. The GA-based SMP successfully decomposed the simulation into two isolated echoes and the parameter estimations were tabulated in Table II.

From Table II, it can be seen that the GA-based SMP can provide parameter estimations close to the optimum, especially for the parameters of arrival time $\tau$ and the center frequency $f_c$ which are the most two sensitive parameters in the reconstruction error. Thus, the parameter estimations provided by the GA-based SMP can be regarded as a good initial guess for the EM method.

Both the echo number and the parameter estimations obtained from the GA-based SMP were then used in EM to obtain the accurate parameter estimations. The final estimated results are tabled in Table II and the final estimated echoes are plotted in Figure 5. For comparison, the original echoes used in simulation (dash line) are also plotted in the figure along with the estimated echoes (solid line). From Figure 5(a) it can be found that the two closely spaced overlapping echoes may easily be erroneously regarded as only one echo. Even though the echo number is estimated correctly, the initial guess is difficult to be chosen. The estimated results of the traditional EM method with two different initial guesses which only have a small difference were also tabled in Table II. The corresponding results were plotted in Figures 6 and 7 respectively.

From the results, it can be seen that an initial guess slightly displaced from the optimum will result in the failure of resolving the closely spaced overlapping echoes. In comparison, the GA-based SMP can provide an initial guess closed to the global optimum and then obtain the accurate results by invoking the EM algorithm.

Furthermore, so as to demonstrate sufficiently that the traditional EM is sensitive to the initial guess for closely spaced overlapping echoes and the GA-based SMP can provide estimates near optimal values robustly, the success rate in recovering the two closely spaced overlapping echoes was adopted. The success rate is the fraction of successfully recover the overlapping echoes. The similarity between a reconstructed echo $\hat{s}$ and an original echo $s$ was measured using the energy error $E = \|\hat{s} - s\|^2/\|s\|^2$. All echoes in the overlapping echoes with an error below 0.02 were considered to be a success recovery. The traditional EM ran 1,000 times with the initial guesses of each parameter randomly chosen from ±10 per cent away from the actual value, except the arrival time was chosen from $\pm 0.1\ \mu s$ away from the actual value. The success rate of the traditional EM was then compared with that of the proposed method when run 1,000 times. For the above-mentioned closely spaced

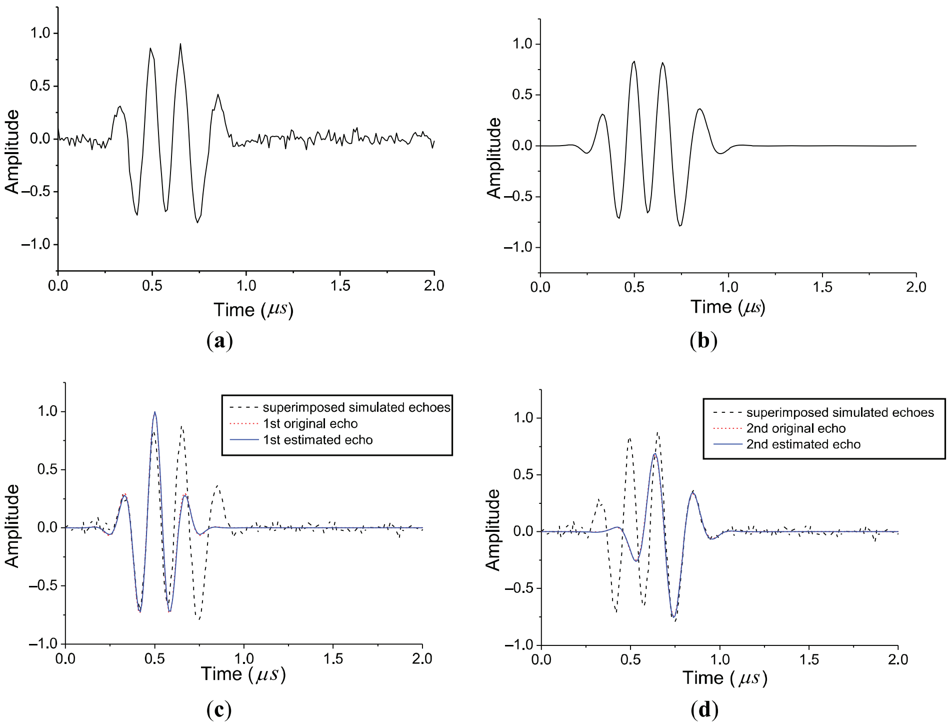
**Table I** Parameters used in the genetic algorithm

| | |
|---|---|
| **Population scale** | 500 |
| **Maximum number of Generations** | 200 |
| **Crossover probability** | 0.8 |
| **Mutation probability** | 0.1 |

**Table II** Parameter estimations for two closely spaced overlapping echoes with SNR 15 dB

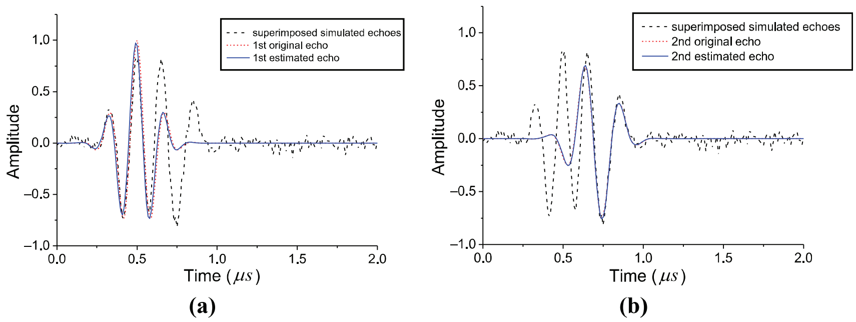
| Echo parameters | Bandwidth factor (MHz)$^2$ | Arrival time ($\mu$s) | Center frequency (MHz) | Phase (rad) | Amplitude |
|---|---|---|---|---|---|
| **Actual parameters** | 40.0000 | 0.5000 | 5.6000 | 0.0000 | 1.0000 |
| | 36.0000 | 0.7000 | 4.3000 | 1.9000 | 0.8000 |
| **GA-based SMP** | 16.0388 | 0.5849 | 5.9115 | 3.4627 | 0.8715 |
| | 14.1408 | 0.6836 | 3.1468 | 1.9117 | 0.3240 |
| **Presented method** | 39.3603 | 0.5005 | 5.6029 | 0.0000 | 1.0269 |
| | 34.8859 | 0.7010 | 4.3080 | 1.9599 | 0.7753 |
| **Initial guess** | 25.0000 | 0.4800 | 6.0000 | 0.0000 | 1.0000 |
| | 25.0000 | 0.6900 | 6.0000 | 0.0000 | 1.0000 |
| **Traditional EM** | 40.8635 | 0.4966 | 5.5743 | 0.1424 | 0.9788 |
| | 37.6251 | 0.7006 | 4.3379 | 1.8837 | 0.8167 |
| **Initial guess** | 25.0000 | 0.4000 | 6.0000 | 0.0000 | 1.0000 |
| | 25.0000 | 0.6000 | 6.0000 | 0.0000 | 1.0000 |
| **Traditional EM** | 28.0521 | 0.6090 | 5.3580 | 3.5538 | 3.4924 |
| | 41.4654 | 0.6283 | 5.1611 | 0.82630 | 3.3520 |

**Figure 5** The estimated results for simulation consisting of two closely spaced overlapping echoes in time with additive white Gaussian noise using the proposed method




**Notes:** (a) The simulated echoes with SNR of 15dB; (b) the estimated echoes; (c) comparison of first estimated echo with original echo; (d) comparison of second estimated echo with original echo

**Figure 6** The estimated echoes extracting from the closely spaced overlapping echoes using traditional EM by giving the initial guess $\Theta^{(0)} = [25, 0.48, 6, 0, 1; 25, 0.69, 6, 0, 1]$




**Notes:** (a) The first estimated echo; (b) the second estimated echo

overlapping echoes, the traditional EM method only has a success rate of about 57.9 per cent, whereas the proposed method has a success rate of 100 per cent.

Meanwhile, as one can also use just the SMP method to obtain initial guesses for the EM method, to demonstrate that the realization complexity of the GA-based SMP is superior to using the SMP itself, the computation time of the presented method was also compared with the method which uses the traditional SMP to obtain initial guess and then use EM to obtain the final estimations. The average computation time of 1,000 times for the presented method to recover the echoes in the above-mentioned overlapping echoes is 114.72 s, whereas the method which obtained the initial guess by the SMP itself needs an average 191.26 s computation time.

In addition, the success rate in recovering two overlapping echoes whose parameters would be randomly chosen for 1,000 times was also tested. The ranges of the parameters are set as following: the bandwidth factor was chosen between 10 and 100. The arrival time was limited between 0 and 1 $\mu$s, and the time delays between the two echoes to were limited be greater than 0.2 $\mu$s. The center frequency was drawn between 1 MHz and 20 MHz, the phase $\phi$ was drawn between 0 and $\pi$ and the

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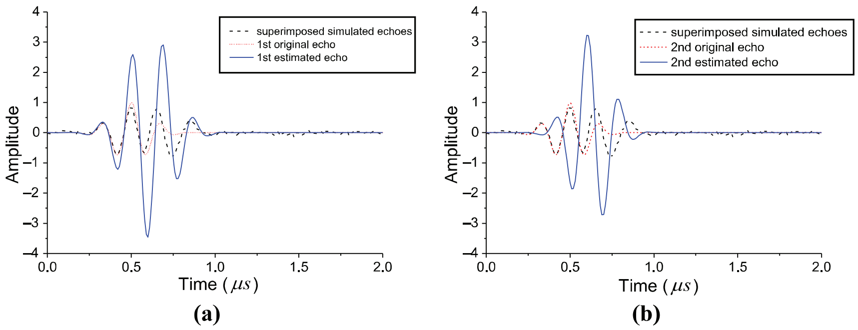
**Figure 7** The estimated echoes extracting from the closely spaced overlapping echoes using traditional EM by giving the initial guess $\Theta^{(0)} = [25, 0.4, 6, 0, 1; 25, 0.6, 6, 0, 1]$




**Notes:** (a) First estimated echo; (b) second estimated echo



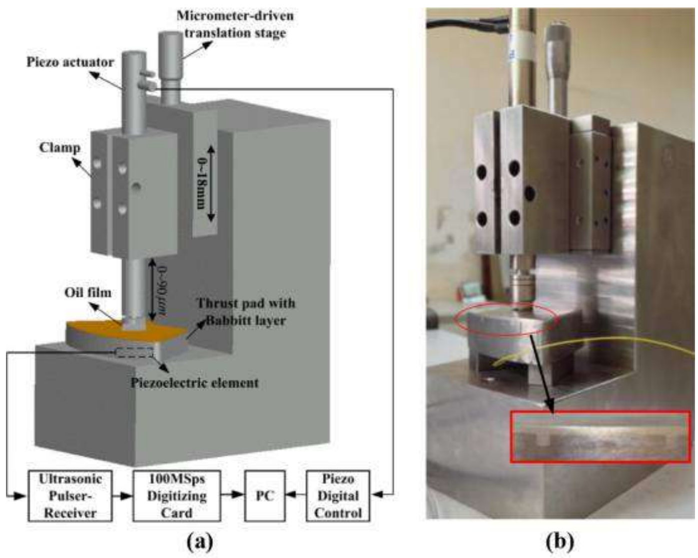
amplitude was drawn between 0.3 and 1. A white Gaussian noise was added to all simulated signals which results in a SNR of 20 dB. We then ran the presented method on all simulated signals. The obtained results showed that the success rate is high up to 94.8 per cent. It demonstrated that the GA-based SMP can provide estimates near optimal values for the EM, and the proposed method has good performance in characterizing overlapping echoes adaptively.

## 4. Application

To validate the effectiveness of the developed method for recovering the overlapping echoes in practice and also demonstrate its power to help to extend the ultrasonic spring model for oil film thickness in four- or multi-layered structures. A calibration apparatus was set up and was shown in Figure 8. The apparatus has two parts: ultrasonic transmit-receive instrumentation and a rig for the accurate control of the lubricant film. The rig is mainly consisted of a micrometer-driven translation stage, a clamp, a piezo actuator and a piezo digital controller. The maximum travel range and the resolution of the micrometer-driven translation stage are 18 mm and 10 $\mu m$, respectively. The piezo actuator was used to adjust the lubricant film in fine step size. In detail, the known lubricant film was set using the following procedure: first, a thick lubricant film was formed and the lubricant film thickness was measured by an ultrasonic Time of Flight (TOF) method which is proved to be very accurate for thick film measurement above 100 $\mu$m. The obtained thick film thickness was treated as the starting number. Then the lubricant film was reduced the integer times of 10 $\mu$m carefully by the micrometer-driven translation stage to the travel range of the piezo actuator. Finally the piezo actuator was controlled by the piezo digital controller to adjust the lubricant film accurately and then form a set of known lubricant film.

The rig was designed to construct with a real thrust bearing. A thin Babbitt layer of 0.35 mm was deposited onto a steel substrate of 20 mm. The ultrasonic transducer used in this work

**Figure 8** Experimental rig for forming a series of known thickness lubricant film




**Notes:** (a) Schematic diagram of the rig; (b) photograph was a thin circle piezoelectric element whose active diameter was $\phi$7 mm and the height is 0.2 mm. The piezoelectric element was bonded directly on the back of the thrust pad using a standard strain gauge adhesive. The center frequency of the piezoelectric element was measured 9 MHz and the bandwidth was 7.5-11 MHz (−6 dB). In practice, being excited by a square wave voltage outputted by the ultrasonic Pulser-Receiver (UPR) at 20 KHz, the piezoelectric element began to vibrate and outputted ultrasound. The outputted ultrasound penetrated the substrate of the sliding bearing and reached the substrate-Babbitt interface where some of the ultrasound was reflected and the other part was transmitted. The transmitted part then reached the Babbitt-oil film layer, similarly, some of the ultrasound was reflected while others was transmitted. Because the Babbitt liner is thin, the ultrasound reflected from the substrate-Babbitt interface was overlapped with the echo reflected from the Babbitt-oil layer. The overlapped echoes were then sampled by a 12-bit, 100 MSps PCI digester card and were acquired into computer memory for post-processing.

The overlapping echo reflected from the substrate-Babbitt interface and from the Babbitt-oil layer was shown in Figure 9 (dash line). Figure 9 also shows the two estimated echoes extracted by the developed method (solid line).

From Figure 9, it can be seen that the estimated echoes are in good agreement with the experimental echoes. The estimated arrival times of the two echoes are 0.4855 $\mu$s and 0.2784 $\mu$s, respectively. Given that the sound speed in the Babbitt layer is 3350 m/s, the corresponding Babbitt layer thickness calculated by time of flight (TOF) is 0.347 mm. This calculated thickness is nearly the same as the actual number (0.35 mm) and it indicates that the presented method estimates the two echoes accurately.

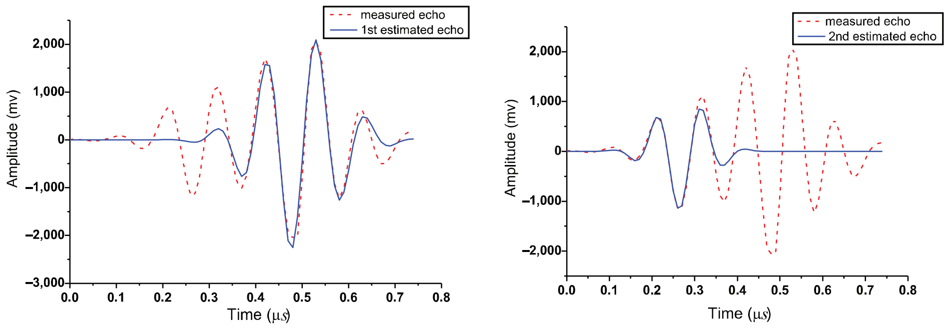
While, when the initial guess $\Theta^{(0)}$ = [20, 0.3, 8, 0, 1000; 20, 0.46, 8, 0, 2000] was provided for the traditional EM method, the estimated results are shown in Figure 10.

Similarly, the estimated arrival times of the two echoes are 0.3990 $\mu$s and 0.4716 $\mu$s, respectively, the corresponding Babbitt thickness calculated is 0.122 mm. The Babbitt thickness calculated does not agree with the actual number and it indicates that the traditional EM method yields the wrong results when giving the initial guess $\Theta^{(0)}$ = [20, 0.3, 8, 0, 1000; 20, 0.46, 8, 0, 2000].

Figure 11 shows the echoes measured from different oil film layers, then the proposed algorithm was then used to separate the overlapped echoes. We got the isolated echoes reflected from Babbitt-oil layer by subtracting the first extracted echo from the overlapped echoes and the results are shown in Fig 12.

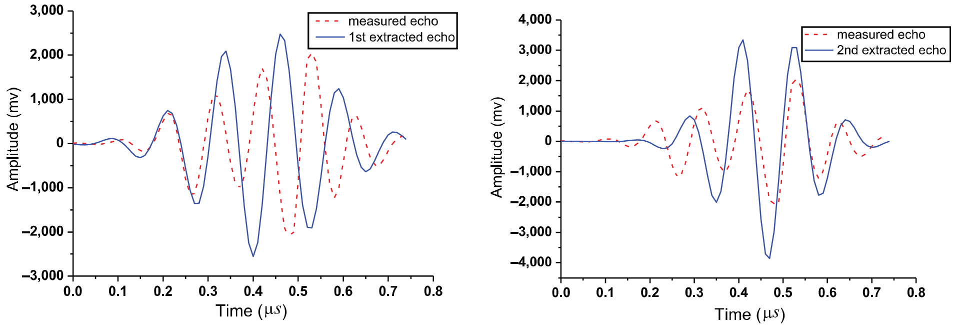
Figure 13 shows the FFT of the echoes reflected from different oil layers. From Figure 13 we can see that the FFT wave shape of the echoes reflected from different lubricant

**Figure 9** The two estimated echoes extracting from the measured echoes by the developed method




**Notes:** (a) First estimated echo; (b) second estimated echo

**Figure 10** The two estimated echoes extracting from the measured echoes using the traditional EM by giving the initial guess $\Theta^{(0)}$ = [20, 0.3, 8, 0, 1000; 20, 0.46, 8, 0, 2000]




(a) (b)

**Notes:** (a) First estimated echo; (b) second estimated echo

**Figure 11** Measured reflected echoes from different thickness films set by the piezo actuator

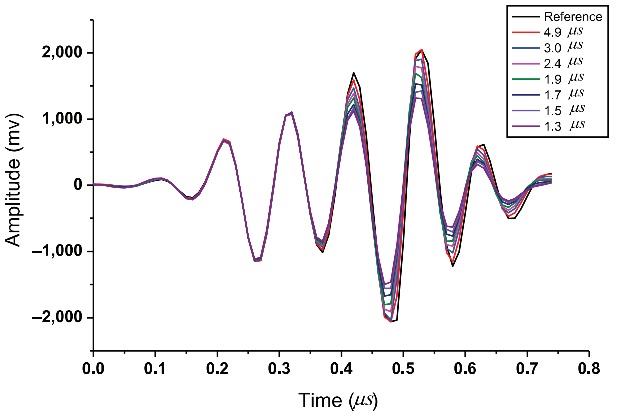



**Figure 12** The extracted echoes reflected from Babbitt-oil layer of different thickness films

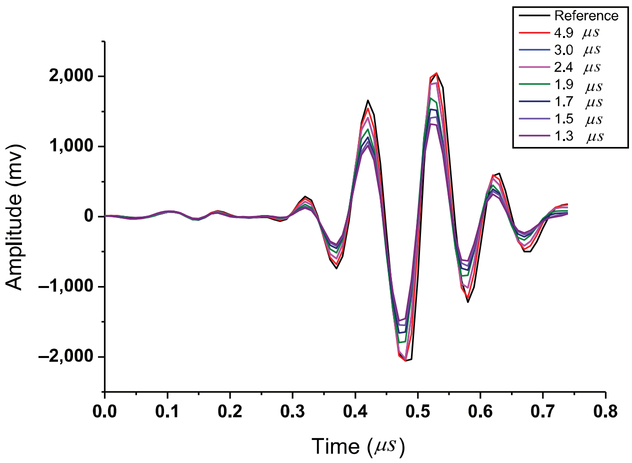
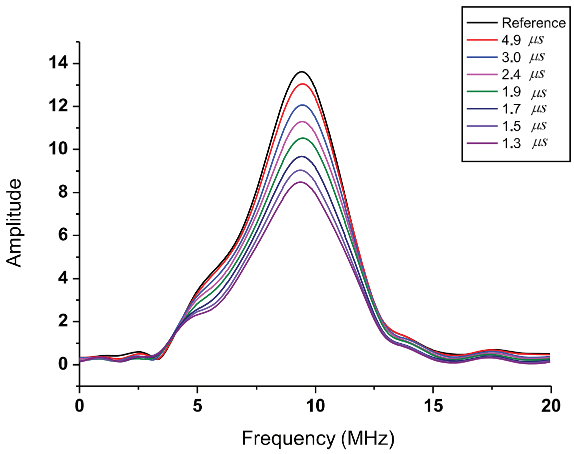



**Figure 13** FTTs of the echoes reflected from Babbitt-oil layer of different thickness films




layers were similar except some differences in the FFT amplitude. This characteristic was just as same as that expected from the theory.

Figure 14 shows the reflection coefficients for different oil layers. Then the lubricant film thickness was calculated by spring model and the results are shown in Figure 15. From Figure 15 it can be seen that the measured lubricant film thicknesses agreed well with the set ones.

## 5. Conclusion

When recovering echoes from overlapping echoes, the traditional EM method requires the echo number and good initial guesses near optimal values to start. Furthermore, for closely spaced overlapping echoes, the results of the EM method are very sensitive to the initial guess. Focusing on these problems, an adaptive method was developed. The adaptive method developed is expected to balance both the computer complexity and the accurate of the results. Then the method was evaluated with both the closely spaced overlapping simulated signals and the overlapping echoes encountered in ultrasonic oil film thickness measurement. Main results that can be obtained are as follows:

- An adaptive method for recovering overlapping echoes was proposed by providing the initial guesses for the traditional EM method using a GA-based SMP approach. The

**Figure 14** Reflection coefficient spectra, included is the reference amplitude spectrum, with vertical scale, to demonstrate the transducer bandwidth

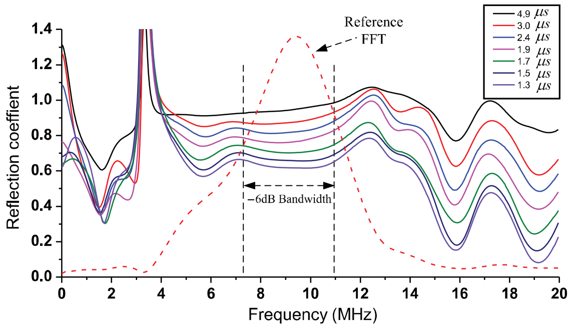
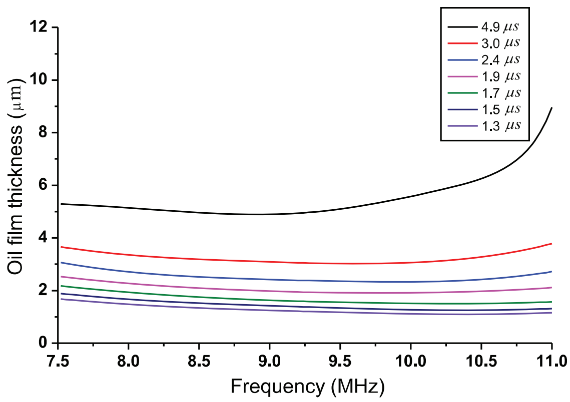



**Figure 15** Oil film thickness obtained from reflection coefficient within the −6dB bandwith



developed method can remove the dependence on the initial guesses for the traditional EM method.

- The validity of the presented method was examined with two closely spaced overlapping echoes and 1,000 different realizations of two overlapping echoes whose parameters are randomly chosen. The results demonstrated that the GA-based SMP can provide estimates near optimal values for the EM, and the proposed method has good performance in characterizing overlapping echoes adaptively and it also has a relative low computation complexity compared with the method providing the initial guess of EM by SMP itself.
- The presented method was applied to separate the overlapping echoes encountered in the ultrasonic measurement of oil film thickness in a thrust bearing with a thin Babbitt liner. The overlapping echoes were separated accurately and it can help to extend the ultrasonic spring model for oil film thickness measurement in multi layer structure.

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