文章编号:1001-2060(2007)03-0264-03

# 基于小波分析的柴-燃联合动力装置信号消噪

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摘 要: 在柴-燃联合动力装置试验台试验过程中, 为消除测量信号中各种噪声和干扰的影响, 减少测量数据试验偏差, 保证试验数据的正常使用, 以3S离合器中间件位移信号为例, 采用db3小波进行5层分解, 选用heursure软阈值进行小波系数阈值量化, 然后进行重构, 从而实现信号消噪。实验分析表明, 利用小波分析进行信号消噪, 原理简单, 实现方便, 具有很高的可靠性, 消噪后的信号为提高整个系统在动力方面机动性的可行性提供了依据。

关 键 词: 船用动力装置; 小波分析; 柴-燃联合; 信号消噪

中图分类号: U664.16; O422.8 文献标识码: B

## 引 言

柴-燃联合(CODOG)动力装置是现代舰船常用的主推进方式之一, 它充分发挥了柴油机经济性好和燃气轮机单机功率大、尺寸小重量轻、从低速到高速转换快等优点。CODOG动力装置在巡航时采用柴油机推进, 在加速时采用燃气轮机推进, 适宜于工况变化范围大, 而且经常在低速工况下航行的大、中、小各种舰船, 动力装置中都得到普遍应用。由于CODOG动力装置试验台的振动和信号干扰, 使实际测量中的信号包含许多尖峰或突变部分, 并且噪声也不是平稳的白噪声, 对这种信号的降噪处理, 用传统的傅立叶变换分析时, 显得无能为力, 因为它不能给出信号在某个时间点上的变化情况。而小波分析属于时频分析的一种, 能够同时在时频域中对信号进行分析, 从而实现信号的降噪, 小波分析对非平稳信号消噪有着傅立叶分析不可比拟的优点。

## 1 小波变换

小波变换是一种信号的时间-尺度分析方法, 它具有多分辨率分析的特点, 而且在时频两域都具有表征信号局部特性的能力, 即在低频部分具有较高的频率分辨率和较低的时间分辨率, 在高频部分具有较低的频率分辨率和较高的时间分辨率, 很适合于探测正常信号中夹带的瞬态反映现象并展示其成份[3]。

在实际运用中连续小波必须加以离散化, 通常把连续小波变换中尺度参数 $a$ 和平移参数 $b$ 的离散化公式分别取作 $a=a_0^j$, $b=ka_0^jb_0$, $(j\in Z)$, 扩展步长 $a\neq 0$ 是固定值, 为方便起见总假定 $a_0>1$, 则对应的离散小波函数 $\Psi_{j,k}(t)$ 为:

$$\Psi_{j,k}(t)=a_0^{-j/2}\Psi\left(\frac{t-ka_0^jb_0}{a_0^j}\right)=a_0^{-j/2}\Psi(a_0^{-j}t-kb_0)$$

离散化小波变换系数则可表示为 $C_{j,k}=\int_R f(t)\Psi_{j,k}^*(t)\mathrm{d}t=\langle f,\Psi_{j,k}\rangle$, 其重构公式为 $f(t)=C\sum_{-\infty}^{\infty}\sum_{-\infty}^{\infty}C_{j,k}\Psi_{j,k}(t)$, $C$ 是一个与信号无关的常数。为了保证重构的精度, 网格点应尽可能密(即 $a_0$ 和 $b_0$ 尽可能小), 因为如果网格点越稀疏, 使用的小波函数 $\Psi_{j,k}(t)$ 和离散小波系数 $C_{j,k}$ 就越少, 信号重构的精度也就会越低。

## 2 小波消噪原理

一般情况下有用信号通常表现为低频信号或是一些比较平稳的信号, 而噪声信号则通常表现为高频信号。一维信号的降噪过程主要进行以下处理, 首先对原有信号进行小波分解, 噪声部分通常包含在高频系统中, 然后对小波分解的高频系数进行阈值量化处理, 最后再对信号重构即可达到降噪的目的。从小波降噪处理的方法上说, 一般有3种处理方法: (1) 强制降噪处理。该方法把小波分解结构中的高频系数全部变为零, 然后对信号进行重构处理, 该方法简单, 且重构后的信号也比较平滑, 但容易丢失信号的有用成份; (2) 默认阈值降噪处理。该方法利用ddencmp函数产生信号的默认阈值, 然后利wdencmp函数进行消噪处理; (3) 给定软或硬阈值降噪处理。在实际的降噪处理过程中, 阈值可

收稿日期: 2006-07-14; 修订日期: 2006-12-29

基金项目: 海军预研基金资助项目(23.8.1.2)

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以通过经验公式获得, 而且这种阈值比默认阈值更据有可信度。在进行阈值量化处理中可用 wthresh 函数进行[2]。

用一维小波进行信号的消噪过程中, 都要用阈值进行小波分解系数的量化处理, 在这种信号处理中, 最重要的环节就是如何选取阈值和如何进行阈值的量化。根据基本的噪声模型, thselect 函数使用 4 种规则来选取阈值, 每一种规则的选择由该函数中所对应的输入参数 tptr 决定, 该函数返回的是所求阈值的值[3~4]。

## 3　小波分析对 CODOG 动力装置信号消噪处理

CODOG 动力装置在运行和切换过程中, 扭矩是考察系统安全性及可靠性的一个重要参数, 同时也反映了 3S 离合器运行的平稳程度; 3S 离合器中间滑移件在啮合及脱开过程中的轴向位移随时间的动态变化从一个侧面反映了切换过程的动态变化。实验过程中对柴油机及燃气轮机端扭矩、转速信号, 以及两台 3S 离合器中间滑移件位移等信号进行实时采集, 通过对比某一时刻柴油机端和燃气轮机端 3S 离合器位移曲线, 可以明确得出完成不同工况切换所需要的时间, 为进一步证明提高整个系统在动力方面的机动性的可行性提供依据。

本文基于 Matlab 软件, 使用小波工具箱为 CODOG 动力装置信号消噪, 所编写的程序简捷明了, 有很强的实用性。利用小波消噪的基本原理, 选用函数 wdencmp 对信号进行消噪处理, 具体形式如下:

xd＝wdencmp(opt, s, wav, n, thr, sorh, keepapp)

其中: xd—消噪处理后的信号; opt＝′gbl′, 并且 thr 是一个正的实数, 则阈值是全局阈值, opt＝′lvd′, 并且 thr 是向量, 则阈值是在各层大小不同的数值; s—原始信号; wav—指定分解时所用的小波; n—小波分解的层数; sorh—指定软阈值(sorh＝′s′)或硬阈值(sorh＝′h′)的选择; tptr—指定阈值选取的规则, 分别为 rigrsure—采用史坦(Stein)无偏似然估计原理(SURE)进行自适应阈值选择, sqtwolog—固定的阈值形式, 它等于 σsqrt(2·log(length(s))), heursure—启发式阈值选择, minimaxi—用极大极小原理选择的阈值; keepapp＝1, 将小波分解的低频系数不作任何处理, keepapp＝0, 对小波分解的低频系数进行阈值量化处理。

CODOG 动力装置试验台某工况下燃气轮机向柴油机端切换时的扭矩和 3S 离合器中间滑移件位移原始信号如图 1 和图 2 所示。从图中可以看出原始信号中包含许多尖峰和突变部分, 并且噪声也不是平稳的白噪声。对这种信号进行分析, 首先需要作信号的预处理, 将信号的噪声部分去除, 提取有用信号。本文中对 3S 离合器中间件位移信号消噪选择 db3 小波, 对原始信号进行 5 层分解, 原始信号分解为 $a_1$ 和 $d_1$, $a_1$ 再分解为 $a_2$ 和 $d_2$, 以此类推。利用 heursure 软阈值进行小波系数阈值量化, 滤掉其中某些频段内的干扰与噪声信号, 软阈值处理是把信号的绝对值与阈值进行比较, 当数据的绝对值小于或等于阈值时令其为零, 大于阈值的数据点则向零收缩, 变为该点值与阈值之差。然后根据小波分解的第五层的低频系数和经过量化处理后的第一层到第五层的高频系数, 进行一维信号的小波重构, 从而消除噪声。扭矩信号的消噪与 3S 离合器中间件位移信号消噪过程相同, 只是由于信号的多样性及噪声强度的不同, 阈值的选取是不同的, 在实际工程应用中需根据不同的分解层数选取合适的阈值, 这样才能更好地消除噪声的影响, 使重构信号能保留原始信号的尖锐和陡峭变化的部分。消噪部分程序如下:

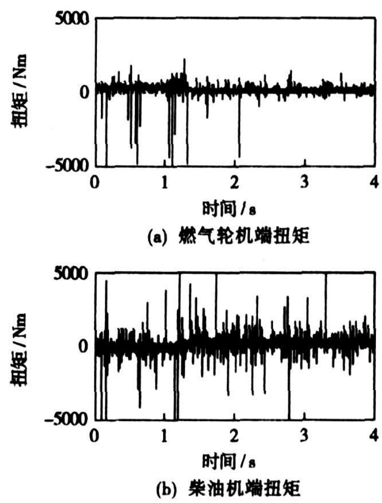


图 1　燃气轮机向柴油机端切换时扭矩原始信号

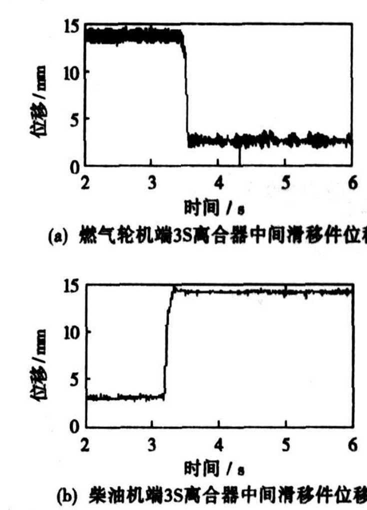


图 2　燃气轮机向柴油机端切换时 3S 离合器中间滑移件位移原始信号

```
[c, l] ＝wavedec(s, 5, ‘db3’);
ca5＝appcoef(c, l, ‘db3’, 5);
```

```
cd5=detcoef(c,l,5);
cd4=detcoef(c,l,4);
cd3=detcoef(c,l,3);
cd2=detcoef(c,l,2);
cd1=detcoef(c,l,1);
cds1=wthresh(cdl,‘s’,0.624),
cds2=wthresh(cd2,‘s’,1.037),
cds3=wthresh(cd3,‘s’,1.422);
cds4=wthresh(cd4,‘s’,1.835);
cds5=wthresh(cd5,‘s’,2.275);
c1=[ca5,cds1,cds2,cds3,cds4,cds5];
s1=waverec(c1,l,‘db3’);
plot(s1)
```

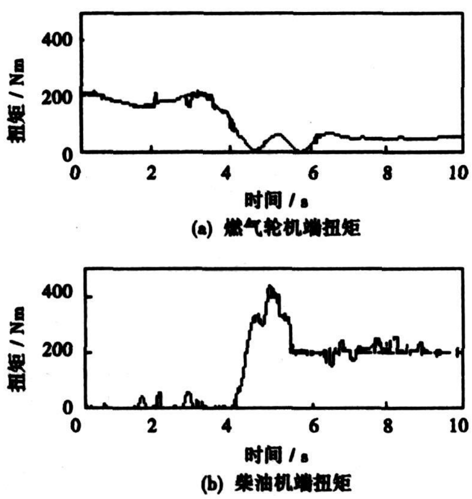


图 3　小波消噪后的扭矩信号

利用小波分析消噪后的扭矩信号和 3S 离合器中间滑移件位移信号如图 3 和图 4 所示，从图中可以看出小波消噪后得到的信号大体上显示了原始信号的形状，明显地除去了噪声所引起的干扰，并可以很好地保存有用信号中的尖峰和突变部分，非常有利于实验结果分析。图 3 可以看出燃气轮机向柴油机端切换时，燃气轮机端扭矩由 200 Nm 降为接近 0 Nm，柴油机端扭矩由 0 Nm 左右上升最后稳定在 200 Nm，由于切换过程存在冲击，导致燃气轮机及柴油机端扭矩在主机切换时刻存在波动，图 3 中从 3～6 s 反映这个过程。图 4 可以看出燃气轮机向柴油机端切换时，燃气轮机端 3S 离合器中间滑移件位移由 14 mm 降为 2 mm，即燃气轮机端 3S 离合器由啮合到脱开，柴油机端 3S 离合器中间滑移件位移由 2.4 mm 升为 14.5 mm，即柴油机端 3S 离合器由脱开到啮合。图 4 中从 3～6 s 反映这个过程，结合图 3 与图 4 可以明确得出主机切换所需时间。在实际 CODOG 动力装置舰船中主机切换过程被设定为约 45 s，考虑到调距桨的反应和完成动作约 22 s。通过在现有 CODOG 实验台上对主机切换过程进行研究，已经得到了切换过程中的许多重要数据，从实验结果分析得出切换过程在极短的时间(不超过 3 s)内完成，冲击扭矩也在允许的范围内，因此改变现有 45 s 的切换时间具有可行性。

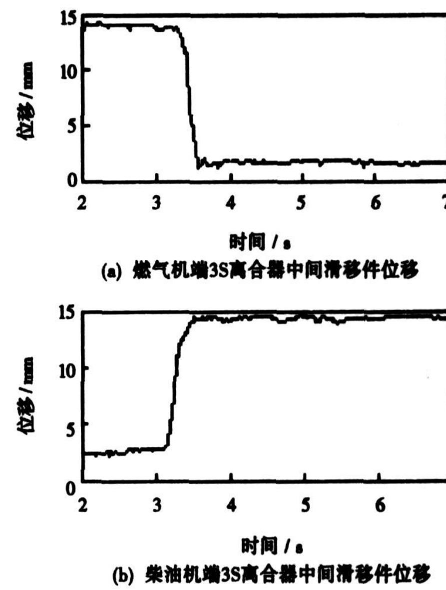


图 4　小波消噪后的 3S 离合器中间滑移件位移

## 4　结　论

利用小波分析对 CODOG 动力装置实验台的信号进行消噪处理，其原理简单，实现方便，有很高的可靠性，能在改善信噪比的同时，又不会引起信号较大幅度的失真，比传统消噪方法具有优势，更有利于对实验结果的分析。通过对消噪后的信号进行分析，得出切换过程在极短的时间内完成，冲击扭矩也在允许的范围内，进一步证明提高整个系统在动力方面的机动性是可行的。

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leaking steam flow patterns in a brush type seal can be virtually neglected. **Key words**: steam turbine, brush-type seal, porous medium model, leaking steam flow rate, numerical simulation

10 MW 氦气轮机涡轮轮盘强度的计算方法＝**A Method for Calculating the Strength of Wheel Disks of a 10 MW Helium Gas Turbine** [刊, 汉] / XU Jun, ZHANG Rui-yan, LIU Han (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036), BAI Xiang-lin (College of Electromechanical Engineering under Harbin Institute of Technology, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —255 ~ 258

To date, the strength calculation and analysis of turbine disks has all along been conducted, using an "equal-thickness ring method" theory. As such a simplification has not taken into account the effect of rigidity of tenon and mortise boss on force transmission, the disk rim stress values thus obtained may sometimes exhibit a sizable error, making it impossible to analyze the stress concentration at the eccentric holes of the disk and at the root of tenon teeth. However, relatively accurate stress analytic results can now be obtained by establishing a real entity model for a wheel disk of complicated structure through the use of software Pro/E and by performing a finite element analysis and calculation, using software ANSYS. By adopting the above-mentioned two methods, calculated and analyzed was a gas turbine disk together with several stages of blades. It has been verified that the "equal-thickness ring method" theory can macroscopically reflect the force-bearing status of the disk. In the meantime, it can be proved that the selection of various parameters for the finite element method is correct, thus providing a technical reference for the strength analysis of other structures of a similar nature. **Key words**: helium gas turbine, wheel disk, strength analysis, contact stress

燃用超低热值燃料的燃气轮机及其热力分析＝**A Super-low heating-value-fuel-fired Gas Turbine and Its Thermodynamic Analysis** [刊, 汉] / WANG Yan-jie, WENG Yi-wu, YIN Juan (College of Mechanical and Power Engineering under Shanghai Jiaotong University, Shanghai, China, Post Code: 200030), SU Shi (Commonwealth Science and Industry Research Organization, Brisbane, Australia, Q14001)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —259 ~263

On the basis of a catalytic combustion mode, presented is a method for utilizing super-low heating-value fuel. A description is given of the structural makeup and working principle of a gas turbine operating on the above fuel and combustion mode along with an analysis of the relevant technical key points. The feasibility of a stable catalytic combustion of the above fuel has been verified through tests. With a gas turbine rated at hundreds of kilowatts serving as an example, calculated and analyzed was a thermodynamic cycle of a gas turbine unit. The results indicate that a gas turbine plant firing the above-mentioned fuel can be realized with an output of effective power, thus providing a feasible method and basis for the research and development of a super-low heating-value-fuel-fired gas turbine system. **Key words**: super-low heating-value fuel, catalytic combustion, gas turbine characteristics, thermodynamic cycle

基于小波分析的柴-燃联合动力装置信号消噪＝**Elimination of Noise from Signals for a CODOG Plant Based on a Wavelet Analysis** [刊, 汉] / TIAN Ying (College of Mechanical and Electronic Control Engineering under Beijing Jiaotong University, Beijing, China, Post Code: 100044), LI Shu-ying (College of Power and Energy Engineering under Harbin Engineering University, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —264 ~266

During the tests of a CODOG (combined diesel or gas turbine) plant on a test stand, to eliminate the impact of various kinds of noise and interference on measurement signals, minimize the test error of measured data and ensure a normal use of the test data, the following measures were taken to realize the elimination of noise from the signals with the displace-

ment signals from the intermediate parts of a SSS clutch serving as an example. The measures include: the use of dB3 wavelets to conduct a 5-layer dissolution and the selection of heursure soft threshold values to perform a quantification of wavelet coefficient threshold values followed by a restructuring of signals. The tests and analysis show that the use of the wavelet analysis for achieving the elimination of noise from the signals is simple in theory, featuring an ease of its realization and an extremely high reliability. The signals after noise elimination provide a solid basis for fostering the feasibility of power-related maneuverability of the whole system. **Key words**: marine power plant, wavelet analysis, CODOG (combined diesel or gas turbine), signal noise elimination

双层滤料过滤床的压降特性研究= **A Study of the Pressure-drop Characteristics of a Dual-layer Filter-material Filtering Bed** [刊, 汉] / YANG Guo-hua, ZHOU Jiang-hua (College of Sea Transportation under the Ningbo University, Ningbo, China, Post Code: 315211)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —267 ~ 269

The working principle and high filtration efficiency of a dual-layer filter-material filtering bed are described along with its low pressure-drop filtration characteristics. The pressure drop at each layer of the above filtering bed was measured during tests. Analyzed were the total pressure drop of the bed layer and the pressure drop characteristics of a hot gas distributor, sand layer and an expanded perlite layer. The results show that the pressure drop of the sand layer accounts for 75% ~ 90% and that of the expanded perlite layer for 5% ~ 22% of the total pressure drop of the bed layer. The pressure-drop characteristics prove that the sand layer provides a surface filtration and the expanded perlite layer a deep bed one. This is the reason why a dual-layer filter-material filtering bed has a filtration efficiency of 99.99% and the bed layer a dust bearing capacity ten times as high as that of a single layer sand bed. **Key words**: high temperature gas, filtration, granular layer, dual-layer filter material

颗粒层除尘器过滤和清灰方式的优化= **Optimization of the Filtering and Deashing Modes for Granular-layer Dust Precipitators** [刊, 汉] / WANG Zhu-liang, LIU Xiao-hang, DU Bin (College of Energy Source and Power Engineering under Jiangsu University, Zhenjiang, China, Post Code: 212013)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —270 ~ 273, 283

Analyzed were the issues affecting the dust removal performance of moving-bed granular-layer dust precipitators due to an increase in clearance between granular layers and also granular particle dislocation etc. Through an optimization effort a granular-layer dust precipitator with a new type of structure and filtering method was created to solve the above issues. Its structure and specific features are described, especially a built-up fluidized bed dust removal mechanism, which can accomplish a quick dust removal from the granular layers. A mathematical model featuring the pressure drop of the dust precipitator bed layer has been established. By way of experiments, the authors have identified the regularity of dust removal from a granular fluidized layer and the filtering performance of the precipitator. Both theoretical research and practice have indicated that the new type of granular-layer precipitators has a better dust removal performance than other granular-layer ones, making it possible to realize an integration of dust removal and deashing as well as to simplify the dust removal process. **Key words**: granular layer precipitator, ash removal, fixed bed, moving bed, fluidized bed

燃煤 $PM_{10}$磁聚并动力学数值模拟= **Numerical Simulation of Magnetic Aggregation Dynamics of Fuel Coal $PM_{10}$** [刊, 汉] / LI Yong-wang, WU Xin, ZHAO Chang-sui, et al (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology under the Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —274 ~ 279

A dual-subregion algorithm has been presented for seeking a solution to the magnetic-aggregation dynamics equation of fu-