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CHARACTERISING CAVITATION NOISE BY WAVELET PACKET REPRESENTATION

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Abstract: Cavitation noise is comprised of burst waveforms resulting from the collapse of cavitating bubbles. Any burst is the mixture of impulses from individual bubbles collapsing in close proximity. A single bubble collapse contributes either to the duration or to the amplitude or to both in the actual mixed burst. Generally, as the severity of cavitation rises, both the amplitude and the duration of impulses in the bursts increase. In any practical system, the vibroacoustic signal of cavitation is blurred by unwanted noise. As the vibroacoustic burst of cavitation is time-frequency concentrated, the orthogonal wavelet packet bases are used to represent cavitation noise. The cavitation bursts are represented as the linear combination of the chosen wavelet packet bases. The wavelet packet coefficients describe cavitation in different frequency components and can discriminate individual bursts in raw data. Furthermore, the wavelet packet decomposition divides the signal into different frequency subbands. Thus the blurred noise can be treated as independently random variables in subbands and is suppressed by thresholding the coefficients.

Keywords: acoustic measurement, cavitation, wavelet packet

1 INTRODUCTION

Cavitation is an important noise source in a fluid or flow system. It is one of the primary factors in causing damage to hydraulic machines, such as pumps, valves, and marine propellers. The acoustic approach to detect cavitation is to pick up the vibration or acoustic energy radiated by bubble collapses. Fourier transform and statistical analysis are the conventional methods of characterizing cavitation noise[1][2]. The original cavitation noise is the mixture of acoustic impulses excited by individual bubble collapses. Because of the limitation of the transient performance and frequency specification of the transducer, the resultant transducing output of a single impulse is an approximately exponential decay cosine wave, usually referred to as an acoustic burst. Accordingly in the vibroacoustic signal of cavitation, the acoustic bursts of collapses at a temporal and geometrical proximity mix together and form an aggregate burst. The single bubble collapse contributes either to the duration or to the amplitude or to both in the actual mixed burst. Because of the random nature of collapses in time and location, it is impossible to expect exactly the same aggregate bursts even under nominally fixed conditions. Thus the frequency components in the vibroacoustic signal of cavitation are time-variant. At different stages of cavitation and in different types of cavitation, the intensity, the occurrence rate and the frequent contents of bursts vary substantially. For example, a strong burst may indicate the occurrence of cavitation cloud shock. To characterize cavitation, it is necessary to identify individual bursts and the measurement of cavitation is based on both the amplitude and the frequency of cavitation noise.

In practice, the vibroacoustic signal of cavitation is blurred with noises from other sources, including the noise from the movement of bubbles prior to collapse, and echoes from previous collapsing acoustic emissions. So part of the noise is not independent of the cavitation signal. Consequently the noise blurred in the raw data is colored rather than white.

As the cavitation acoustic burst waveform is time-frequency concentrated, the time-frequency concentrated orthogonal wavelet packet bases are used to approximate the cavitation bursts. A burst is represented by the linear combination of the chosen wavelet packet bases. Each wavelet packet basis expresses one frequency component. Thus, the vibroacoustic signal of cavitation is divided into different frequency subbands through wavelet packet decomposition. In each subband, the blurred noise can be roughly treated as an independent normal distribution random variable, and so the noise then can be suppressed by thresholding the wavelet packet coefficients.

2 THE VIBROACOUSTIC SIGNAL OF CAVITATION

The acoustic pressure wave P(t) from collapsing bubbles can be approximated by an exponential expression:

$$P(t) = \begin{cases} P^{*} e^{-\frac{t}{a}} & (t \geq 0) \\ P^{*} e^{\frac{t}{b}} & (t < 0) \end{cases} \tag{2-1}$$

Here, it is assumed that the acoustic wave reaches the transducer at its peak P^{*} at time t=0. a and b are time constants of the order of $10^{-6} \sim 10^{-7}$ seconds[3]. As transducers have limited response frequency band, and usually have a second-order or higher transient response property, (this is the typical of a piezoelectric transducer), the output $c_i(t)$ from a vibration or acoustic transducer picking up the acoustic pulse is an oscillating damped waveform :

$$c_i(t) = \begin{cases} A \cdot P^{*} e^{-\frac{t-t_i}{a}} + B \cdot P^{*} e^{-\frac{t-t_i}{t}} \cdot \cos(w(t-t_i) + q_0) & (t-t_i) \geq 0 \\ A \cdot P^{*} e^{\frac{t-t_i}{b}} + B \cdot P^{*} e^{\frac{t-t_i}{t}} \cdot \cos(w(t-t_i) + q_0) & (t-t_i) < 0 \end{cases} \tag{2-2}$$

where t_i is the arrival instant of the acoustic wave from the collapsing bubbles. Constants A and B are associated with the transducing coefficient of the transducer, the time constant t is determined by the dynamic response property, and the oscillating frequency w reflects the feature frequency of the transducer: it approximately equals the cut-off frequency. The relationship between t and w is

$$t = \frac{1}{x \cdot w} \quad (0 < x < 1) \tag{2-3}$$

The resultant output at time t is the sum of all N bursts arriving up to and including time t:

$$c(t) = \sum_{i=1}^{N} c_i(t) \tag{2-4}$$

As the acoustic bursts decay exponentially, at any time t, only the pressure impulses arriving within the time neighbourhood of around t length can significantly contribute the resultant output: either to the extension of impulse duration or to the enhancement of the impulse amplitude or to both in the mixed burst. The different blended waveforms of three bursts collapsing at different time (assumed having the same zero initial phase) are illustrated in Fig. 1 (a)-(c). An exceptional case is shown in Fig. 1 (d): the approximate mute impulse produced by two bursts at nearly opposite initial phases .

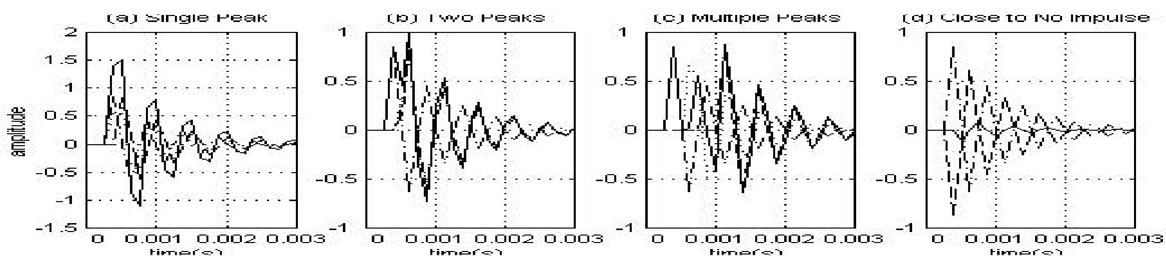

Fig. 1 The schematic composite waveforms of acoustic bursts

3 WAVELET PACKET REPRESENTATION

Let $j_1^0(t), j_1^1(t)$ be the scaling and wavelet function of a family of orthonormal wavelet bases. If $h(n), g(n)$ are the associate pair of conjugate mirror filters, the orthonormal wavelet packet bases are constructed as[4]:

$$j_{j+1}^{2p}(t) = \sum_{n=-\infty}^{+\infty} h(n) j_j^p(t - 2^j n)$$
$$j_{j+1}^{2p+1}(t) = \sum_{n=-\infty}^{+\infty} g(n) j_j^p(t - 2^j n) \qquad (3\text{-}1)$$

The two indices j, p indicate the position of the wavelet packet basis in the admissible wavelet packet tree structure: j, the depth of the tree; p, the order at the depth. Like wavelet bases, wavelet packet bases are concentrated in time and frequency and at the same time they divide the frequency axis into separate intervals of various sizes. Another distinguished feature of wavelet packet bases is that they are highly oscillatory compared with wavelet bases. Here the wavelet packet bases at the same depth are chosen to approximate the vibroacoustic signal of cavitation as they partition the frequency axis into uniform intervals. Suppose the support interval of the wavelet function is [0, N], the discretized version of the signal representation $\tilde{f}(i)$ is given by

$$\tilde{f}(i) = \sum_{m=n-N}^{n} \sum_{p=0}^{2^j-1} w_j^p(m) \cdot j_j^p(i - 2^j m) \quad (m \ge 0, \quad i \ge 0) \qquad (3\text{-}2)$$

where n is the integer part of $(i/2^j)$. The wavelet packet coefficient is

$$w_j^p(n) = \; < f(i),\ j_j^p(i - 2^j n) > \; = \sum_{i=0}^{\infty} f(i) j_j^p(i - 2^j n) \qquad (3\text{-}3)$$

So the approximate vibroacoustic signal at an interval of $(2^j n, 2^j(n+1) - 1)$ is determined by the wavelet packet coefficients $w_j^p(n-l), l = 0,..., N$. Suppose

$$P_{j_j^p}^2(m) = \sum_{i=0}^{2^j-1} (j_j^p(m+i))^2 \quad (m = 0,1,..., N) \qquad (3\text{-}4)$$

In terms of wavelet packet coefficients, the average power of the vibroacoustic signal in the pth subband at the interval of $(2^j n, 2^j(n+1) - 1)$ is

$$P\tilde{f}_p^2(n) = \sum_{m=n-N}^{n} (w_j^p(m))^2 \cdot P_{j_j^p}^2(m) \qquad (3\text{-}5)$$

4 CHARACTERIZATION PROCEDURES

The practical vibroacoustic signal cav(t) contains cavitation waveforms $c(t)$ and noises $n(t)$ from other sources, i.e.

$$cav(t) = c(t) + n(t) \qquad (4\text{-}1)$$

As the different wavelet packet bases concentrate on different frequency intervals, the white part in $n(t)$ is uniformly diffused in coefficients over all wavelet packet bases and the colored part in $n(t)$ is mainly contributing to the coefficients in the corresponding frequency subbands. In the coefficients of each wavelet packet, the noise can be treated as an independently normal distribution random variable. Hence the noise can be suppressed by thresholding the coefficients[5]. So

$$c(t) = cav(t) - n(t) \approx f(t) \qquad (4\text{-}2)$$

$f(t)$ is reconstructed from wavelet packet coefficients after thresholding. The discretized $f(i)$ is obtained by equation (3-2). $Pf_p^2(n)$ contours the cavitation power distribution in the pth subband. The minima of

$Pf_p^2(n)$ position the bursts. A typical feature of the inception and development of cavitation lies in that there exists bursts of impact shock in the cavitation acoustic noise. Suppose $p_{max}(i)$ are the maxima in $Pf_p^2(n)$, and $p_{min}(i)$ the minima, the criteria for cavitation detection is

$$|p_{max}(i) - p_{min}(i)| > e(p) \tag{4-3}$$

$e(p)$ can be determined by either statistical or empirical estimation of system properties.

5 RESULTS AND CONCLUSIONS

Experiments on the characterisation of cavitation have been conducted on the H400 Cavitation Demonstration Unit. A hydrophone (Brüel and Kjær, Type 8103) is used as the acoustic transducer by installing it on the outside wall of the venturi-tube at the downstream flow. The cut-off frequency (-3db) of the hydrophone is about 180 kHz with a charge sensitivity of 0.09 pC/Pa. The amplifier output sensitivity is set at 100 m v/Pa. Three groups of raw data are sampled at 10kHz respectively under the conditions of no cavitation, inception and moderate cavitation. The raw data and the corresponding root power distribution $Pf_p(n)$ from the denoised wavelet packet coefficients are shown in Fig.2. The wavelet packets constructed from the DAUB 3 wavelet are used at depth 3.

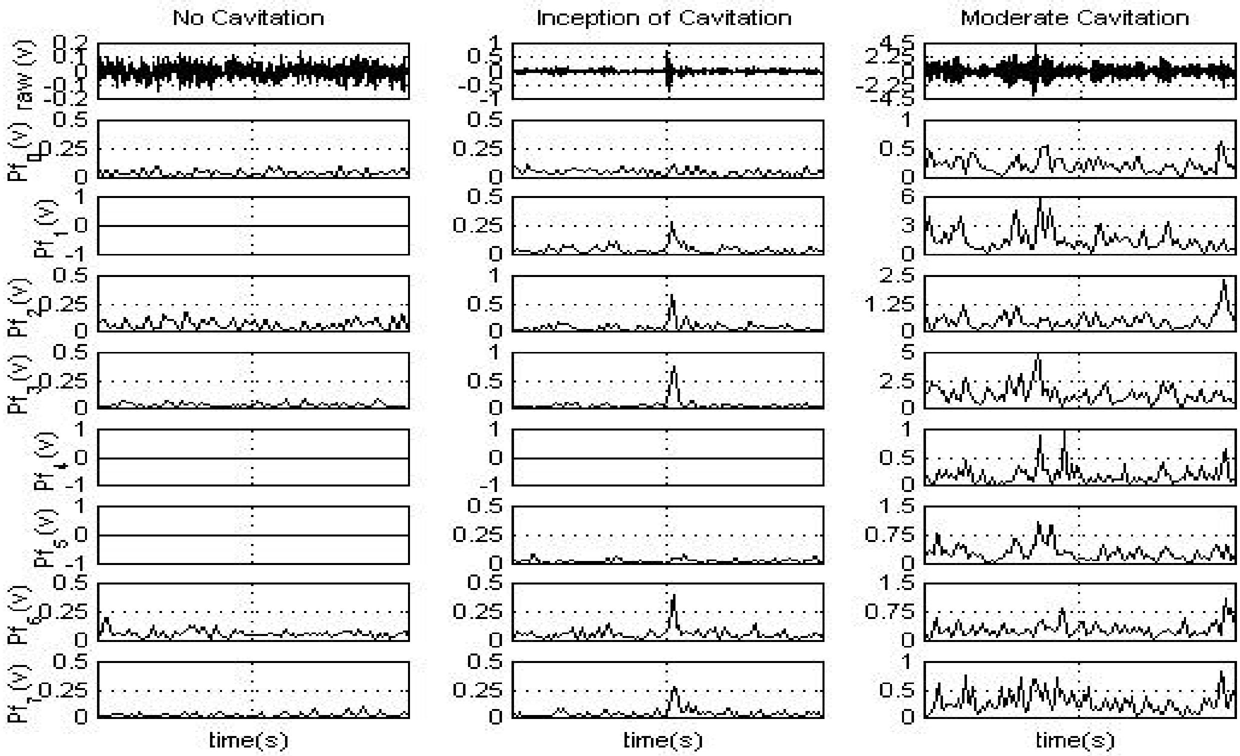

Fig. 2 Raw data of cavitation and their power distribution over different wavelet packet bases

When cavitation occurs, bursts are clearly present in the raw data. The wavelet packet coefficients are quite sensitive to the bursts, as indicated by simultaneous peaks in adjacent wavelet packets. The pulses of $Pf_p(n)$ position the bursts over time and over frequency as well. As analyzed above, both the noise intensity and frequency contents of cavitation vary over time. By using the wavelet packet representation of the vibroacoustic signal of cavitation, it is possible to characterize and classify cavitation precisely, and define the measurement of cavitation as a function of $Pf_p(n)$ and wavelet packet index p.

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