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带可调式前置导叶轴流泵空化性能试验

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摘要: 以一台带可调式前置导叶轴流泵为研究对象,在闭式试验台上进行了非额定工况的空化性能试验,揭示了前置导叶对轴流泵空化性能及进出口压力脉动的影响。空化性能曲线表明:安装前置导叶后,水力损失增加,扬程下降,但临界汽蚀余量减小,空化性能得到改善;前置导叶由负角度向正角度调节时,虽然扬程逐渐降低,但抗汽蚀性能得到增强。压力脉动分析结果表明:空化初生时,设置前置导叶后进出口压力脉动幅值均增加,且峰值主要出现在叶频及其谐频处,临界空化与空化严重时,进口压力脉动主要集中在低频处,出口则呈现宽频脉动特性;流量降低时,泵内流态紊乱,前置导叶对压力脉动幅值影响较小,且脉动峰值出现位置随前置导叶角度变化而改变。

关键词: 轴流泵; 前置导叶; 汽蚀余量; 压力脉动

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Experiment on Cavitation Performance of Axial Pump with Adjustable Inlet Guide Vanes

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Abstract: In order to reveal the influences of variable inlet guide vanes (IGVs) on cavitation performance of axial pump under off-design conditions, experiment was conducted in a closed test rig at the Pump Station Laboratory of Wuhan University. Both the operating conditions with and without IGVs and the situations when the angles of IGVs were changed were researched. The angles of IGVs were adjusted by bolts. The cavitation performances were obtained and the unsteady pressure pulsations collected by pressure sensors which installed in pump inlet and outlet were analyzed based on fast Fourier transform. The results showed that when the pump device was assembled with IGVs, pump head was reduced due to more energy losses were induced. However, the cavitation performance was improved. At the same time, the critical net positive suction head was decreased and the cavitation performance was enhanced as the angles of IGVs were adjusted from negative to positive values. The pressure pulsation results showed that when cavitation occurred, pressure amplitude was magnified both in pump inlet and outlet when IGVs were set up, and the pressure peak appeared mainly in blade frequency and its harmonic frequencies as a result of the influence of rotating of impeller. With the development of cavitation, pressure pulsation aggregated in low frequency in inlet and appeared broadband feature in outlet. When mass flow rate was decreased, the pressure amplitude discrepancy shrank and the pressure peak depended on the angles of IGVs.

Key words: axial pump; inlet guide vane; net positive suction head; pressure pulsation

引言

轴流泵高效区较窄,故灌溉排水泵站无法长期在高效区运行而产生效率低下问题[1]。为改善轴流泵非设计工况运行条件,国内外学者进行了大量试验工作与数值模拟研究[2-10]。DOHMEN 等[2]提出双进口喷嘴的设计方法。唐慧等[3-4]采用开缝翼形、J 型槽等方式提高轴流泵小流量下的水力性能。

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导叶调节作为旋转机械中常见的调节方式，也逐渐运用于轴流泵中。钱忠东等[5-6]提出后置导叶角度调节能够拓宽水泵稳定运行区。FENG 等[8-9]通过数值模拟研究了前置导叶对轴流泵水力性能的影响。

水力机械中的空化与压力脉动问题也不容忽视，尤其非设计工况下，空化常带来异常压力脉动，导致机组振动加剧，影响安全运行，文献[11-20]就此进行了研究。TSUGAWA[13]通过试验研究了一种三维反设计轴流泵发生空化时转轴振动及轮缘压力脉动情况。张德胜等[15-16]分析了叶轮叶顶区空化特性，同时通过数值模拟研究了轴流泵空化现象及压力脉动分布情况。卢加兴等[17]研究了离心泵小流量工况空化时的压力脉动特性。而目前关于前置导叶对轴流泵空化性能影响的研究较少。

本文采用试验的方法，研究非设计工况下带可调式前置导叶轴流泵的空化性能，分析前置导叶角度对临界汽蚀余量的影响，阐明压力脉动随空化发展的变化情况。

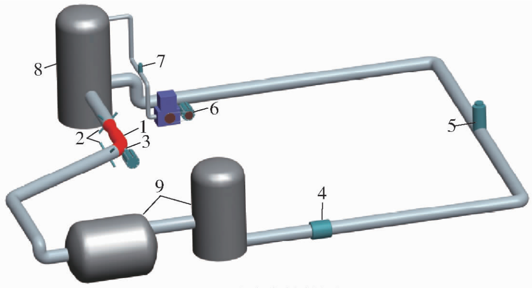
1　试验装置

空化试验在武汉大学水资源与水电工程科学国家重点实验室的闭式试验台上进行，装置系统如图 1 所示。该闭式试验台由水泵装置、空化发生装置和数据采集系统构成。水泵装置包括叶片角度可调节的前置导叶、叶轮和后置导叶，泵内流量由管路中的电磁控制闸阀调节。空化发生装置包括真空泵及调节阀，同时，调节阀前端设有真空表以确定轴流泵进口真空度。数据采集系统连接着沿水泵进出口断面均匀布置的压力传感器，其不确定度小于 0.66%；电磁流量计不确定度小于 0.36%；以及电动机转轴外侧的 HLD09 型转矩转速传感器不确定度小于 0.54%。

模型泵如图 2 所示，具体参数如下：叶轮直径 300 mm，叶轮叶片数 $Z_r=3$，后导叶片数 $Z_s=5$。在进口导水锥外壳上设置前置导叶，其角度可调节，叶片数 $Z_i=4$，当叶片方向沿泵轴时，角度为 0°，叶片倾斜方向与叶轮旋转方向一致时，角度为正，反之，角度为负，具体定义见文献[8]，前置导叶叶片可调角度为 -10°、0°、10°。水泵主要设计参数为：设计流量 $Q_d=370.33$ L/s，扬程 $H=3.283$ m，额定转速 $n=1\,450$ r/min，为研究非设计工况不同流量下前置导叶角度对空化性能的影响，试验选择 $0.85Q_d$、$0.30Q_d$ 两种流量进行。

2　试验方法

机组启动前，检查管路，通过空载试验进行转矩



(a) 试验台结构图


(b) 试验台实物图

图 1　试验装置图

Fig. 1　Setup of test rig

1. 水泵装置　2. 压力传感器　3. 转矩转速传感器　4. 电磁流量计　5. 电磁控制闸阀　6. 真空泵　7. 调节阀　8. 压力罐　9. 稳压罐

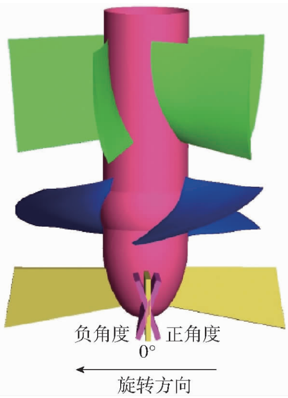


图 2　模型泵示意图

Fig. 2　Model sketch of axial pump

转速传感器的调零；同时确定数据采集系统参数。试验时，首先通过调节电磁闸阀使管路内流量达到试验要求，后打开真空泵，改变调节阀开度，真空表指数每下降 0.005 MPa 采集一次数据，为确保安全运行，当扬程陡降时停止该工况的测试。每次采集数据均重复进行 3~5 次，以减小测量误差。完成一个角度的性能测试后，调节前置导叶角度，重复进行空化试验。运行过程中，由于电路不稳定等因素，转速无法保持恒定，与额定转速间存在差异，因此采用比例率定律对参数进行换算[21]。

3　结果与讨论

3.1　空化性能

图 3 为 $0.85Q_d$ 工况前置导叶不同角度的空化

性能曲线，从图中可以看出，随着汽蚀余量的减小，曲线均存在明显的水平段、上升段、下降段。汽蚀余量较大时，轴流泵扬程保持不变，此时空化尚未对水泵性能产生显著的影响；随着汽蚀余量的减小，扬程略微上升，这可能是因为随着空化的发展，空泡附着在叶片上，具有光顺叶片表面的作用[22]；汽蚀余量进一步降低时，扬程急剧下降，这是由于空化迅速发展，空泡增多，堵塞流道所致。对比无前置导叶与前置导叶 0°的曲线，可以发现设置前置导叶后，扬程降低了 10%，这是因为导叶叶片的存在增加了泵内能量损失。同时可以发现，前置导叶负角度向正角度调节时，扬程降低，可见负角度工况下水力性能较优，这是由于前置导叶角度改变了轴流泵进口速度分布所致[8]。

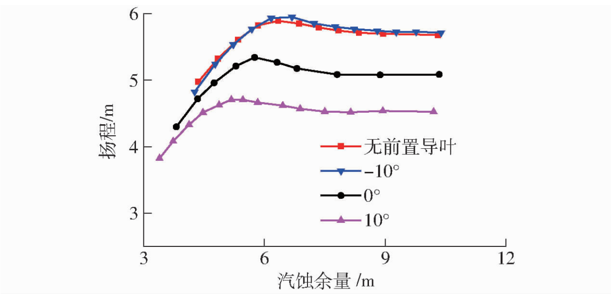


图 3　0.85Q_d工况空化性能曲线

Fig. 3　Cavitation performance curves under 0.85Q_d

以扬程下降 3% 对应的汽蚀余量作为临界汽蚀余量[23]，无前置导叶以及前置导叶 -10°、0°、10°时计算结果分别为 5.11、5.18、4.65、4.23 m。由此可知，0.85Q_d工况时，与无前置导叶相比，前置导叶 0°的临界汽蚀余量明显降低，说明前置导叶具有改善轴流泵空化性能的作用；前置导叶 -10°向 10°调节时，临界汽蚀余量减小，说明前置导叶正角度调节能够进一步增强水泵抗汽蚀性能。

0.30Q_d工况前置导叶不同角度的空化性能曲线如图 4 所示，由图可知，前置导叶负角度时轴流泵水力性能同样优于正角度，这与 0.85Q_d工况的规律一致；同时可以发现，随着汽蚀余量的减小，扬程只维持了极短的水平段，随后迅速下降，这是因为小流量泵内流态紊乱，对空化敏感，空化一旦发生水力性能急剧恶化。

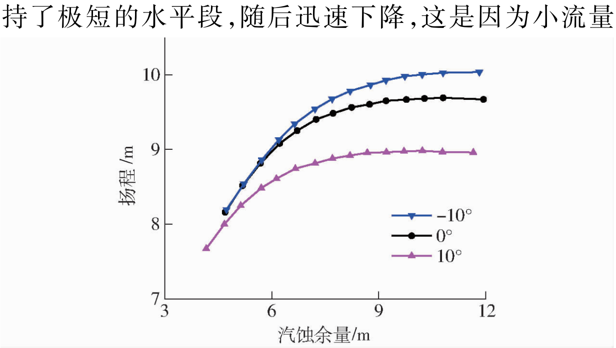


图 4　0.30Q_d工况空化性能曲线

Fig. 4　Cavitation performance curves under 0.30Q_d

3.2　压力脉动

为研究空化时前置导叶对轴流泵压力脉动的影响，选择空化初生、临界空化及空化严重 3 种情况进行分析，以第 1 测点（轴流泵进口压力最大的试验点）作为空化初生点；以临界汽蚀余量对应的工况点作为临界空化点；以扬程下降 15% 对应工况点作为空化严重点。采用快速傅里叶变换对进出口相同监测点压力脉动进行分析。以压力系数 C_p 表征监测点处压力脉动，其计算公式为

$$C_p = \frac{p - \bar{p}}{0.5\rho U_{tip}^2} \tag{1}$$

式中　p——监测点压力，Pa

$\bar{p}$——采样时间内监测点压力均值，Pa

ρ——流体密度，kg/m^3

U_{tip}——叶轮叶顶圆周速度，m/s

以叶频倍数 $Z_r = f/f_n$ 表征频率无量纲参数，其中 f 为测点脉动频率，f_n 为泵轴旋转频率，其公式为

$$f_n = \frac{n}{60} \tag{2}$$

图 5 为 0.85Q_d工况运行一段时间后，4 个旋转周期内轴流泵进口压力脉动时域图。由图可知，空化初生时，前置导叶的存在增大了压力脉动幅值，且由负角度向正角度调节时，幅值进一步增大，可见正角度工况水泵进口受不良流动因素干扰较严重。临界空化与空化严重时，有无前置导叶与前置导叶不同角度间压力脉动幅值时域差异较小。

图 6 为 0.85Q_d工况运行一段时间后，4 个旋转周期内轴流泵出口压力脉动时域图。从图中可以发现，空化初生时，无前置导叶与前置导叶 0°出口压力脉动幅值差异较小，但前置导叶 10°与 -10°时脉动幅值均有所增大，10°时幅值增大尤其明显。临界空化时与空化严重时，设置前置导叶均降低了出口压力脉动幅值，但前置导叶正负角度调节时产生的影响不同。

图 7、8 分别为 0.30Q_d工况运行一段时间后，4 个旋转周期内轴流泵进、出口压力脉动时域图。与 0.85Q_d相比，小流量时进出口压力脉动幅值均增大。同时可以发现，虽然前置导叶各角度压力脉动幅值差异较小，但随着空化发展，进、出口压力脉动幅值均有所上升。

图 9 为 0.85Q_d工况轴流泵进、出口压力脉动频域图。由图可知，对于水泵进口，空化初生时，设置前置导叶后压力脉动幅值明显升高，且幅值随着角

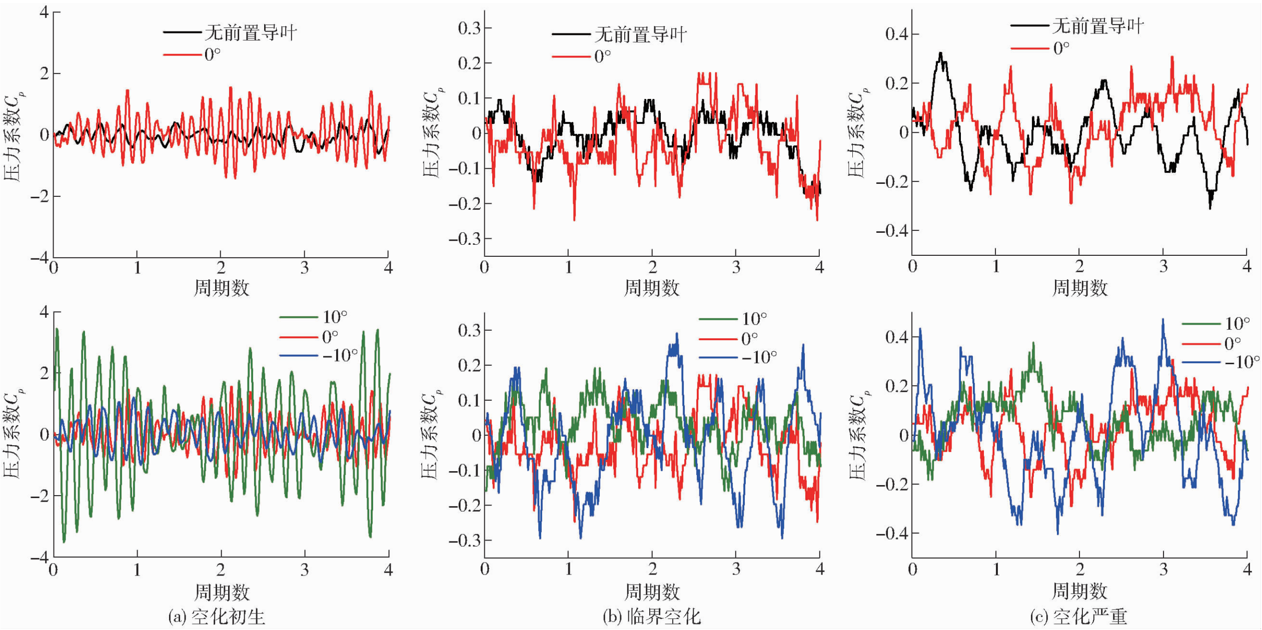


图 5 0.85Q_d工况进口压力脉动时域图

Fig. 5 Unsteady pressure pulsation of inlet sensor under 0.85Q_d

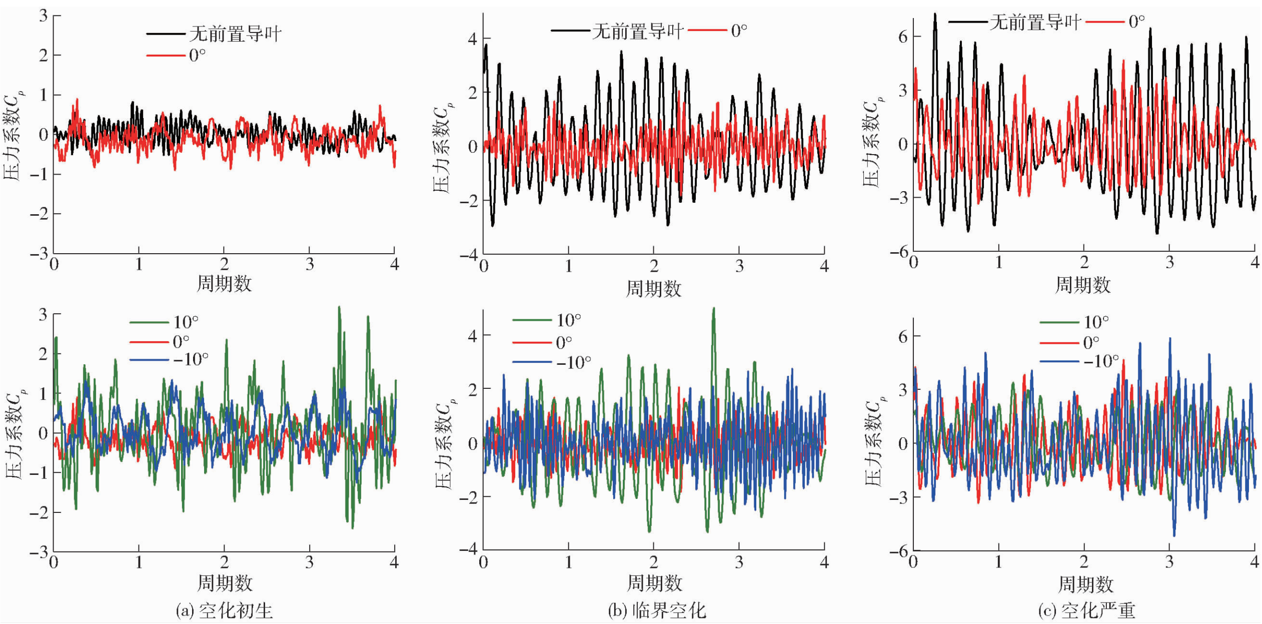


图 6 0.85Q_d工况出口压力脉动时域图

Fig. 6 Unsteady pressure pulsation of outlet sensor under 0.85Q_d

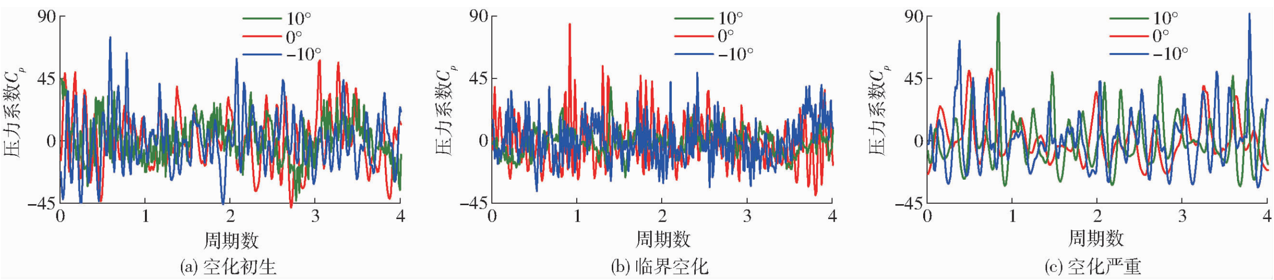


图 7 0.30Q_d工况进口压力脉动时域图

Fig. 7 Unsteady pressure pulsation of inlet sensor under 0.30Q_d

度增大而增大,这与时域图规律一致;同时,压力脉动峰值主要出现在叶频及其倍数处,可见叶轮转动对上游流场的影响。临界空化与空化严重时,压力脉动均以低频脉动为主,可能是受到了叶片背面流动分离及空泡脱落的影响。对于水泵出口,空化初生时,与进口相似,前置导叶增加了压力脉动幅值,

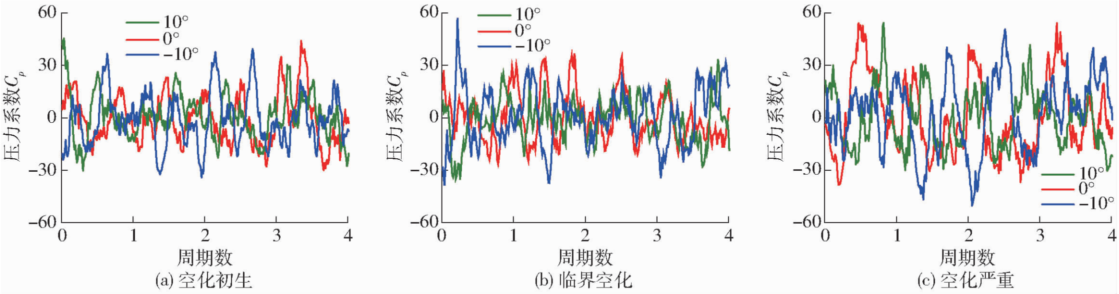


图 8　0.30Q_d工况出口压力脉动时域图

Fig. 8　Unsteady pressure pulsation of outlet sensor under 0.30Q_d

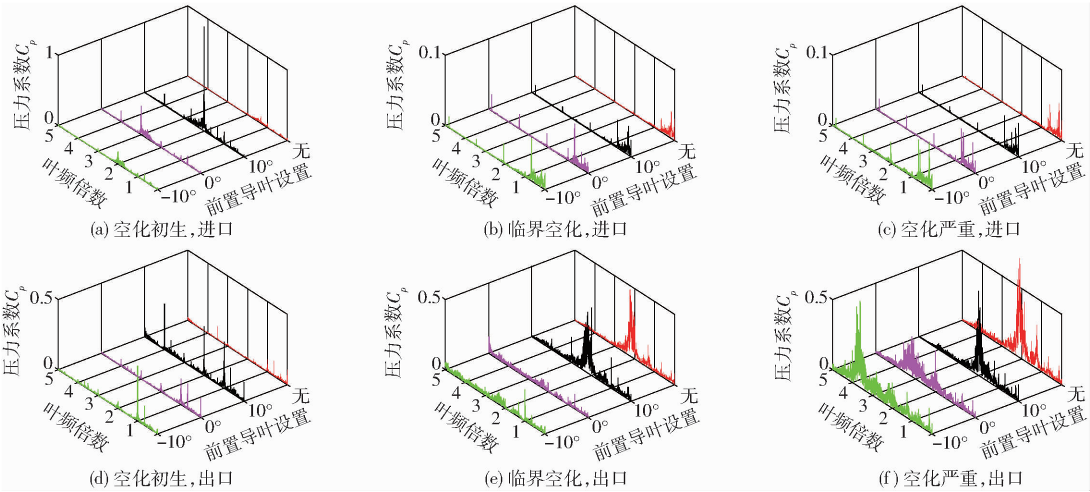


图 9　0.85Q_d工况压力脉动频域图

Fig. 9　Frequency spectrums of unsteady pressure pulsation under 0.85Q_d

同时可以发现，叶频处均出现了较大的脉动峰值，这体现了叶轮旋转对水泵出口流场的影响。临界空化时，无前置导叶与前置导叶 10°均出现了较大范围的宽频脉动；空化严重时，这种宽频脉动同样出现在前置导叶 −10°与 0°工况下，并且在幅值和范围上进一步加剧，这可能是由于空泡大量产生和溃灭，对出口造成干扰所致。

图 10 为 0.30Q_d工况轴流泵进、出口压力脉动

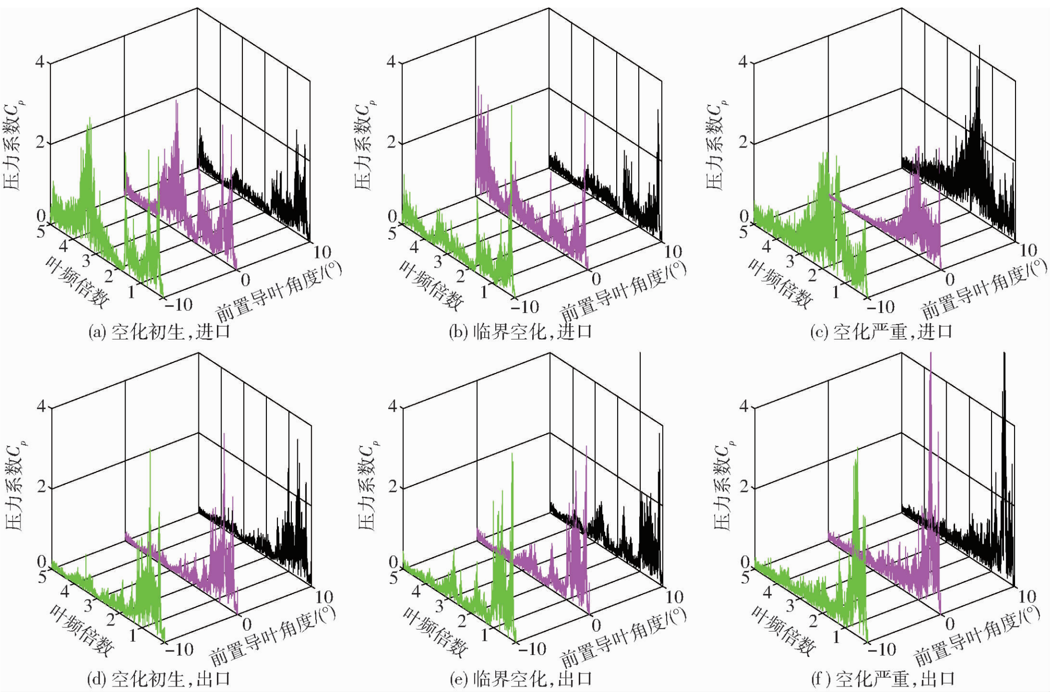


图 10　0.30Q_d工况压力脉动频域图

Fig. 10　Frequency spectrums of unsteady pressure pulsation under 0.30Q_d

频域图。从图中可以发现,不同空化程度下,进口压力均呈现宽频脉动特征,峰值出现位置因前置导叶角度而异。对于出口,压力脉动主要分布在低频区,且峰值随着空化程度加剧而增大。

4 结论

(1)小流量工况下,与无前置导叶相比,前置导叶 0°时轴流泵水力损失增加,扬程下降,但抗汽蚀性能增强;且随着前置导叶向正角度调节,临界汽蚀余量降低,前置导叶 10°时空化性能最优。

(2)通过压力脉动时域图发现,空化初生时,前置导叶增大了轴流泵进、出口压力脉动幅值;随着空化的发展,不同前置导叶角度间进口压力脉动幅值差异缩小,同时,前置导叶的存在明显降低了出口压力脉动幅值。流量降低时,前置导叶对泵内压力脉动时域的影响变小。

(3)通过压力脉动频域图发现,空化初生时,受叶轮转动的影响,轴流泵进、出口压力脉动峰值主要出现在叶频及其谐频处;随着空化的发展,叶频及其谐频处峰值逐渐消失,进口压力脉动以低频为主,出口压力则呈现宽频脉动。流量降低时,压力脉动在不同前置导叶角度下均以宽频脉动为主。

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