文章编号: 1000-5870(2003)04-0091-03

腐蚀管线的剩余寿命预测

帅 健

(石油大学机电工程学院, 北京 102249)

摘要: 预测管线的腐蚀变化趋势及腐蚀对管线结构完整性的危害是评价管线剩余寿命的关键步骤。将影响管线剩余寿命的各种因素看成是分布各异的随机变量, 建立了预测管线失效的概率数学模型。利用这一模型, 研究了腐蚀速率、缺陷深度、管道壁厚和工作压力等因素对管线可靠性的影响。结果表明, 各参数的不确定性越大, 管线的可靠性越低; 缺陷深度在腐蚀缺陷形成初期, 对管线的可靠性有很大影响, 而随着时间的推移, 腐蚀速率将对管线的可靠性有较大影响。对一条输油管线, 基于管线腐蚀检测数据, 对 1 km 长度的管道进行失效概率统计分析得到的腐蚀速率能够对管线全线的安全状况做出合理预测, 从而为管线的进一步维修与检测提供参考资料。

关键词: 油气管线; 腐蚀; 剩余寿命; 失效概率; 预测; 数学模型

中图分类号: TE 988.2, O 211.9 文献标识码: A

引 言

确保服役输油气管线的安全运营是实现管线高效、节能输油的关键。然而, 随着管线使用年限的增加, 管线的腐蚀现象越来越严重, 给管线的安全运行带来威胁。为了预测整个管线的腐蚀情况, 确知腐蚀对管线结构完整性的危害程度, 有必要对腐蚀趋势进行预测, 以了解管线的剩余寿命, 确保管线的安全使用。但是, 由于管线腐蚀的复杂性, 很难掌握各因素对腐蚀的影响规律。采用概率统计的方法预测管线腐蚀有一定的合理性[1]。因此, 笔者建立管线失效预测的概率数学模型, 对管线可靠性的影响因素进行分析。

1 数学模型

描述管线腐蚀缺陷的两个基本参数是缺陷的深度和长度, 腐蚀缺陷在周向的宽度对管线的承压能力影响不大, 一般不须考虑。在腐蚀作用下, 缺陷的范围在逐年扩大。记最近一次(T_0 时刻)检测到的缺陷深度和长度分别为 d_0 和 l_0, 若考虑径向腐蚀速率 R_d, 轴向腐蚀速率 R_l, 则在服役若干年后(T 时刻)的腐蚀缺陷的深度和长度分别为

$$d = d_0 + R_d(T - T_0), \tag{1}$$

$$l = l_0 + R_l(T - T_0). \tag{2}$$

其中, d, d_0, l, l_0 的单位为 mm; R_d 和 R_l 的单位为 mm/a; T 和 T_0 的单位为 a。缺陷管线的爆破压力方程为[2]

$$p = \bar{\sigma}\frac{2t}{D}\left[1 - \frac{d_0 + R_d(T - T_0)}{\delta}\right] \Big/ \left[1 - \frac{d_0 + R_d(T - T_0)}{\delta}\frac{1}{M}\right]. \tag{3}$$

其中

$$M = \begin{cases} \sqrt{1 + 0.6275\left(\dfrac{l}{\sqrt{D\delta}}\right)^2 - 0.003375\left(\dfrac{l}{\sqrt{D\delta}}\right)^4}, \\ \qquad \left(\dfrac{l}{\sqrt{D\delta}}\right)^2 \leqslant 50; \\ 0.032\left(\dfrac{l}{\sqrt{D\delta}}\right)^2 + 3.3, \quad \left(\dfrac{l}{\sqrt{D\delta}}\right)^2 > 50. \end{cases}$$

$$\bar{\sigma} = S_{MYS} + 68.95.$$

式中, p 为缺陷管线承受的最大安全压力, MPa; $\bar{\sigma}$ 为管材的流变应力, MPa; D 为管道直径, mm; δ 为管道壁厚, mm; M 为鼓胀因子; S_{MYS} 为规定最小屈服极限, MPa。

建立随机变量 p 的极限状态函数

$$z = p - p_1. \tag{4}$$

式中, p_1 为工作压力, MPa。

如果 z 为正值, 则管线是安全的; 如果 z 为负值, 管线将失效。将式 (3)代入式 (4), 得

收稿日期: 2003-02-17

基金项目: 中国石油天然气集团公司中青年创新基金项目(CX1998-27)

作者简介: 帅健(1963—), 男(汉族), 湖北黄梅人, 教授, 博士, 博士生导师, 从事工程力学及油气储运系统安全工程研究。

$$z=\bar{\sigma}\frac{2t}{D}\left[1-\frac{d_0+R_d(T-T_0)}{\delta}\right]\Big/\left[1-\frac{d_0+R_d(T-T_0)}{\delta}\frac{1}{M}\right]-p_1. \quad (5)$$

由式(5)可确定管线服役一段时间后的失效概率。式(5)为非线性的极限状态函数,且各随机变量不一定为正态分布,按照可靠性理论,用雷-菲法求解式(5)决定的失效概率或可靠性指标[3]。

2 腐蚀管线剩余寿命的影响因素分析

影响管线失效概率的主要参数为缺陷深度 d_0,工作压力 p_1,径向腐蚀速率 R_d 以及壁厚 δ。以可靠性指标作为衡量指标,分析其变化规律。图 1~4 分别为 R_d, d_0, p_1 及 δ 对可靠性指标的影响结果。图 1 表明径向腐蚀速率在短期内(10 a 以下)对可靠性指标影响不大,但从长期来看,该因素对腐蚀管线的失效作用影响很大。图 2 表明缺陷深度 d_0 在出现缺陷初期对可靠性指标影响很大,但随着时间的推移,其影响越来越小。图 3 和图 4 表明,腐蚀管线的可靠性指标随着工作压力及管线壁厚的变异系数的增大而降低,各参数的不确定性越大,管线越易失效。总之,腐蚀管线的可靠性随服役时间的延长而降低。

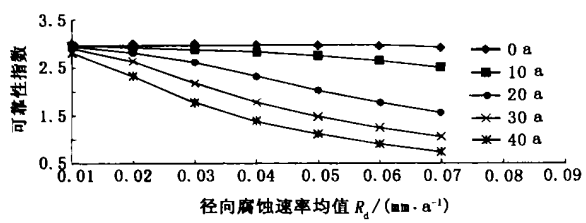

图 1 径向腐蚀速率 R_d 对可靠性指标的影响

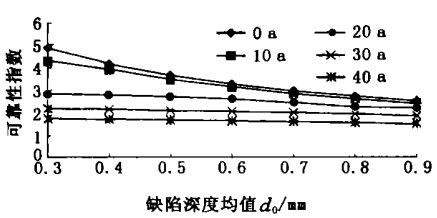

图 2 缺陷深度 d_0 对可靠性指标的影响

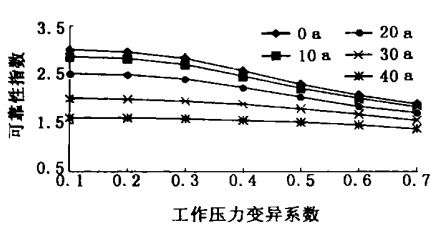

图 3 工作压力 p_1 对可靠性的影响

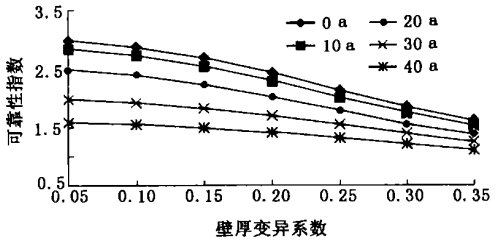

图 4 壁厚 δ 对可靠性的影响

3 管线的腐蚀速率和失效概率预测

对某一段经腐蚀检测后的输油管线的剩余寿命进行预测。该段管线的上站出站压力均值为 4.137 MPa,变异系数为 0.019,推荐采用 Gumbel Ⅰ型极大值分布;下站进站压力均值为 1.897 MPa,变异系数为 0.265。管材的屈服极限均值为 390.8 MPa,变异系数为 0.113;拉伸强度均值为 526.2 MPa,变异系数为 0.029,推荐采用正态分布。

3.1 腐蚀速率

有两种数据来源可以得到腐蚀速率数据。一种方法是对历年来管线的维修记录进行统计分析,这种方法得到的缺陷尺寸数据较准确,但这样的数据很少,不能全面反映管线的腐蚀情况;第二种方法是对历次检测数据进行统计分析,这种方法得到的是管线腐蚀状况的全面反映,是管线全线腐蚀速率数据的合理来源。对该管线腐蚀检测数据的统计分析表明,管线腐蚀缺陷深度服从指数分布,而缺陷长度服从对数正态分布。该管线的运营时间为 20 a,将缺陷深度和腐蚀影响长度分别除以检测时管段运营时间,得到管线腐蚀速率的基本数据。管线腐蚀缺陷的轴向腐蚀速率的统计是针对整个管段的,均值为 159.90 mm/a,变异系数为 0.265。径向腐蚀速率的统计针对每公里长度的管道[3],沿管线每公里管道的腐蚀速率的均值如图 5 所示。

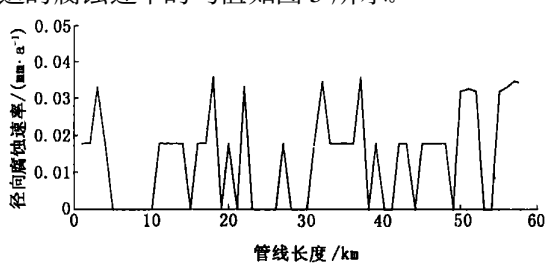

图 5 管道沿线每公里管道的腐蚀速率均值

3.2 失效概率预测

图 6 为该段管线的失效概率发展趋势预测。图中,0 a 表示检测的当时,目标失效概率定为 10^{-3}[4]。

从图中可以看出，在检测的当时，离上站 6 和 18 km 处，失效概率超过目标值。由于腐蚀的影响，在 10 a 之内，距上站 22，31，38 km 地段的失效概率将逐步发展至接近目标失效概率；20 a 后，距上站 49～58 km 地段的失效概率也会接近于目标失效概率。对于超过目标失效概率的管段，建议采取两种措施选择一些重点部位（如检测出的严重缺陷部位）予以监测。一种方法是局部检修，即对检测出的严重缺陷予以修复，修复后管线的失效概率将明显降低；另一种是再次检测，由于检测的精度受多种因素影响，再次检测可进一步准确确定管线的腐蚀缺陷状况，且用两次时间间隔较近的检测数据的统计分析结果作为腐蚀速率的基本数据，可以提高预测的精度。

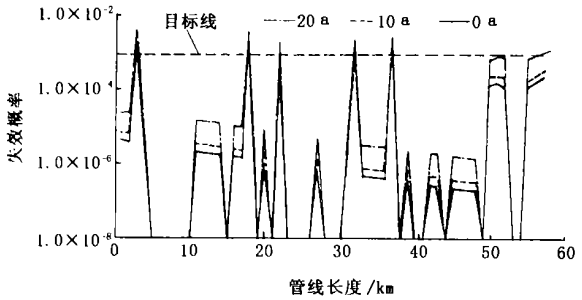

图 6　管道沿线失效概率预测

4　结　论

（1）建立了基于腐蚀速率的管线剩余寿命的数学概率预测模型，利用此模型能够预测管线失效概率（或可靠性）及其发展趋势。

（2）影响管线可靠性的因素有缺陷深度、腐蚀速率、管线壁厚、工作压力等。各参数的不确定性愈大，失效的可能性愈大。

（3）短期内，缺陷深度对管线的可靠性影响很大，而随着时间的推移，腐蚀速率的影响将起主要作用。

（4）提出了对每公里管线进行失效概率预测的方法，能够对管线全线的安全状况做出预测。确定合理的管线腐蚀检测周期能够提高预测的精度。

参考文献：

[1] TORBJORN Sotberg, MORK Kim J, SERGHIOS Barbas. ISO standard pipeline transportation systems: Reliability-based limit state methods[R]. Proceedings of the Ninth International Offshore and Polar Conference, Brest, France, 1999. 325－330.

[2] ASME. B31G manual for assessing remaining strength of corroded pipes[S]. American Society of Mechanical Engineers, 1996.

[3] 帅健，许葵. 腐蚀管线的失效概率评定方法[J]. 石油学报，2003，24(4)：86－89.

[4] TORBJORN Sotberg, *et al*. The superb project: Recommended target safety levels for limit state based design of offshore pipelines[S]. OMAE-Volume V, Pipeline Technology, 1997. 71－77.

（责任编辑　沈玉英）

（上接第 90 页）

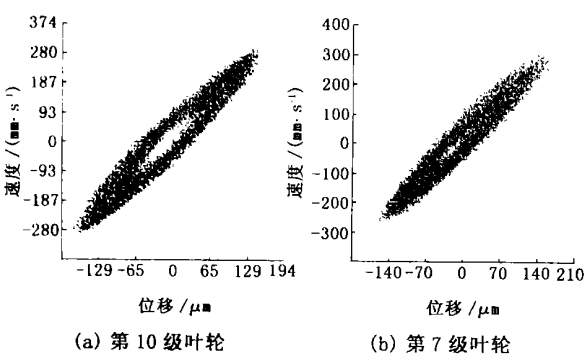

图 6　存在故障的注水泵机组的相图

从相图上可以清楚地判断出注水泵第 7 级的状态好于第 10 级。

3　结　论

（1）利用相图对注水泵机组进行故障诊断是对常规故障诊断方法的一种有效补充。该方法是一种全新的判断设备零部件状态的方法，可以准确地、定性地判断离心式注水泵机组是否存在故障，解决了使用常规诊断方法难以解决的问题。

（2）利用混沌相图分析方法，将设备的状态演化为几个阶段，进而定性地判断设备部件的运行状态。

（3）将该方法与其他参数结合，可以提高诊断精度，为大型离心式设备的故障诊断提供一种有效手段。

参考文献：

[1] 黄润生. 混沌及其应用[M]. 武汉：武汉大学出版社，2000. 31－34.

[2] 袁小宏，史东锋. 奇异值分解技术在齿轮箱故障诊断中的应用[J]. 振动、测试与诊断，2000，20(2)：91－96.

（责任编辑　沈玉英）

/ *TIAN Li-zhu, ZHANG Lai-bin and WANG Zhao-hui. College of Mechanical and Electronic Engineering in the University of Petroleum, China, Beijing* 102249/ *Shiyou Daxue Xuebao*, 2003, 27(4): 88 ~ 90

Abstract: The water injection pump units are widely used in the production of oilfields. Based on the chaos theory, the evolvement state of water injection pump units from normal to bifurcation and then to chaos was researched. The corresponding relation between phase portrait and variance of vibration signal was obtained. A new method for judging qualitatively pump fault with phase portrait was presented. This method was tested using the vibration data of water injection pump units in Liaohe Oilfield, and a good result has been obtained. The phase portrait and variance combined with other characteristic parameters can effectively improve the diagnosis precision.

Key words: phase portrait; variance; chaos theory; water injection pump; fault diagnosis

PREDICTION METHOD FOR REMAINING LIFE OF CORRODED PIPELINES/ *SHUAI Jian. College of Mechanical and Electronic Engineering in the University of Petroleum, China, Beijing* 102249/ *Shiyou Daxue Xuebao*, 2003, 27(4): 91 ~ 93

Abstract: Prediction of the corrosion in pipeline and the effects of corrosion on the structural integrity of the pipeline is a key step for the assessment of the remaining life of a pipeline. A probabilistic mathematical model was set up, taking various kinds of factors influencing the remaining life of a pipeline as random factors. The effects of corrosion rate, defect depth, thickness of pipe and operation pressure on pipeline reliability were investigated with this model. It is concluded that the larger the uncertainty of each parameter is, the lower the pipeline reliability will be. Defect depth has a significant influence on the pipeline reliability in the early corrosion period, while radial corrosion rate has the most significant contribution to pipe corrosion in the course of time. The corrosion rate per kilometer of pipeline obtained after statistic analysis on inspection data can be used to predict the failure probability along the whole pipeline. The obtained result is of reference to further maintenance and inspection of pipeline.

Key words: oil and gas pipeline; corrosion; remaining life; failure probability; prediction method; mathematical model

FUZZY FATIGUE RELIABILITY ANALYSIS ON STRUCTURAL MEMBERS OF OFFSHORE PLATFORM IN ICE AREA/ *FANG Hua-can, JIA Xing-lan and DUAN Meng-lan. College of Mechanical and Electronic Engineering in the University of Petroleum, China, Beijing* 102249/ *Shiyou Daxue Xuebao*, 2003, 27(4): 94 ~ 97

Abstract: In order to design offshore fixed production platforms used in ice area and assess their safety reliability in service, the methods for estimating the safety fatigue life and analyzing the reliability of structural members of offshore platform in ice area were proposed by means of fuzzy mathematics and fatigue life experiments. The calculation method for random fatigue stress range resulted from sea wave loads and sea ice loads in ice area was given, and the analysis method for fatigue cumulative damage of structural members of offshore platform was provided. The Miner rule was modified in consideration of its fuzziness. Based upon the corrected Miner rule, an estimation method for safety fatigue life was developed. A new analysis model for fuzzy fatigue reliability was established. According to this new model, an assessment method for fuzzy fatigue reliability of structural members of offshore platform in service was provided. The fatigue life experiments and practical calculation example show that the calculated result of the fatigue life using the new calculation method is more close to the experimental result than that by means of ordinary certainty Miner rule.

Key words: ice area; offshore platform; structural member; fatigue life; reliability analysis; fuzzy mathematics

REVEALMENT OF SULFIDE LINKAGES IN ASPHALTENE OF SULPHUR-RICH OIL USING NICKEL BORIDE REDUCTION METHOD/ *ZHU Jun, GUO Shao-hui and LI Shu-yuan. State Key Laboratory of Heavy Oil Processing in the University of Petroleum, China, Beijing* 102249/ *Shiyou Daxue Xuebao*, 2003, 27(4): 98 ~ 101

Abstract: A novel desulphurizing agent, nickel boride (Ni_2B), was used to study the sulfide linkages in sulphur-rich asphaltene. The products from Ni_2B reduction of asphaltene were dominated by saturated hydrocarbons including large numbers of n-alkanes and cyclic biomarkers. The parameters of biomarkers in the products are similar to those of saturated hydrocarbon in crude oil, which indicates that these organic sulphur compounds in asphaltene may be the precursor of hydrocarbons.

Key words: nickel boride reduction method; sulphur-rich oil; asphaltene; desulphurization; biomarker; saturated hydrocarbon

OIL-WATER INTERFACIAL TENSION OF VACUUM RESIDUA FRACTIONS OF DAQING CRUDE OIL / *PENG Bo, LI Ming-yuan, ZHAO Suo-qi, et al. State Key Laboratary of Heavy Oil Processing in the University of*