涡激振动计算技术规程

中国能源建设集团山西省电力勘测设计院有限公司

目录

1.波和浪致的涡激振动

1.1 输入参数及参数计算

（1）基本参数

基本参数应包含：钢管直径 D、钢管厚度 t、杆件长度 L、流体速度 u、波浪有益高度 Hs、波浪周期 Tp、水深 d、钢材弹性模量 E、截面惯性矩 I。

（2）杆件两端固定类型参数 An

杆件两端固定类型参数 An 可根据下表进行取值：

表 1-1 杆件两端固定类型参数 An

杆件两端固定类型	A_n 取值
固定-自由	3.52
铰接-铰接	9.87
固定-铰接	15.40
固定-固定	22.40

（表格来源于论文《大型深水导管架建造工况条件下的杆件涡激振动评估_卫旭敏》）

（3）海水的粘滞系数和密度

不同温度下，海水的运动粘滞系数和密度如下表所示：

表 1-2 不同温度下海水运动粘滞系数和密度

海水运动粘性系数

水温 C°	运动粘性系数（$10^{-6}m^2/S$）	密度（kg/m^3）
5	1.5650	1048.1
10	1.3563	1047.3
15	1.1907	1046.3
20	1.0565	1045.1
25	0.9479	1043.6

（4）单位有效质量 Me

对于导管架而言，结构内部没有水，因此单位长度结构内部的水质量为 0，

即 Mw=0。

对于单桩而言，结构内部充水，因此单位长度结构内部水的质量可通过下式计算：

$$M_w = \pi \rho_w r^2$$

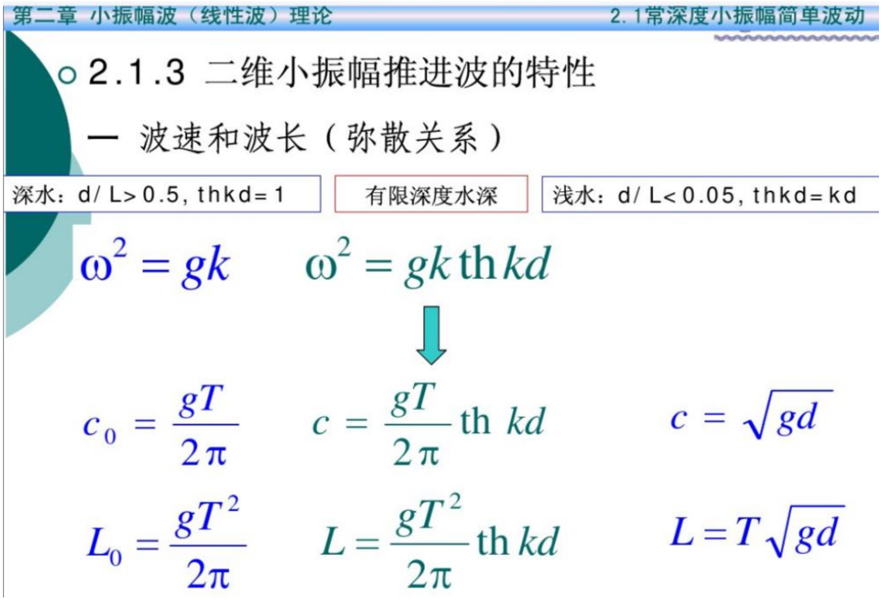
有效的结构质量为单位长度的钢材质量 Ms，计算方法如下：

$$M_s = \pi \rho_s D t$$

基于以上计算，单位有效质量的计算方法为：

$$M_e = M_s + M_w$$

1.2 波数的迭代计算



波数迭代计算			
波浪周期	T	10.4	s
水深	d	22	m
深水波数	k	0.037207161	
修正波数	k	0.0478	m-1
参数 1	（2π/T）^2	0.364630178	
参数 2	gktanh(kh)	0.366520397	
比值	（gktanh(kh)）/（（2π/T）^2）	1.005183936	
复核	（2π/T）^2≈gktanh(kh)	OK	

已知波浪周期和水深，可计算得到深水波数 k：

波浪的角频率ω计算方法如下：

$$\omega = \frac{2\pi}{T_p}$$

波数 k 可通过下式计算：

$$k = \frac{\omega^2}{g}$$

依据 NB／T10105-2018 中 F.0.3 节中的相关规定，有限水深的波数应通过下式计算：

$$\left(\frac{2\pi}{T}\right)^2 = g \times k \times tanh(kd)$$

其中，T 为波浪周期，k 为波数，d 为水深。

依据上式可以迭代出波数 k，偏差保证在 0.99~1.01。

1.3 构件的一阶自振频率

注意：此处只能用用于构件（杆件）的一阶自振频率计算，对于单桩整体结构不使用此处公式计算频率，可通过 SACS 进行计算。

波浪波长 L 计算方法如下：

$$L = \frac{2\pi}{k}$$

波浪参数 1 为 kd；

波浪参数 2 为 thkd 为：

$$\mathrm{thkd} = \frac{e^{kd} - e^{-kd}}{e^{kd} + e^{-kd}}$$

修正波长 L’为：

$$L' = thkd \times L$$

一阶自振频率f_1为：

$$f_1 = \frac{A_n}{\pi}\sqrt{\frac{EI}{M_e L^4}}$$

1.4 判断浪和流的涡激振动主导

波浪高出海面的高度 z 一般为-0.5Hs~0.5Hs，因此取 0.5Hs 和-0.5Hs 对应 z 的两个极值，取 0.5Hs 时，对应波浪速度 Vm 最大；取-0.5Hs 时，对应波浪速度 Vm 最小。

依据 DNVGL-RP-C205 中的 9.7.1.2 条的规定，流速比例可通过下式计算，当α＞0.8 时，为流主导；当α＜0.8 时，为浪主导。

9.7.1.2 The current flow velocity ratio is defined as:

$$\alpha = \frac{u_c}{u_c + v_m}$$

If α > 0.8, the flow is current dominated and the guidance in [9.6] is applicable.

其中波浪速度 Vm 可由水质点运动轨道有益速度（非波速）Vs 替代，其中 Vs 的计算方法可根据 DNVGL-RP-C205 中的 9.7.1.4 计算。

9.7.1.4 In irregular flow the K_C number can be calculated by substituting v_m with the significant fluid velocity, v_s. Based on sea state parameters, the significant velocity in deep water can be estimated as:

$$v_s(z) = \frac{\pi H_s}{T_p} e^{k_p z}$$

where:

H_S = significant wave height

T_P = peak wave period

k_P = wave number corresponding to a wave with period T_P

z = vertical coordinate, positive upwards, where mean free surface is at z = 0.

1.5 流主导的涡激振动危险性判断

1.5.1 参数计算

(1)约化速度V_R

约化速度V_R的计算可依据 DNVGL-RP-C205 中的 9.1.6 节：

9.1.6 Reduced velocity

For determination of the velocity ranges where the vortex shedding will be in resonance with an eigen frequency of the member, a parameter V_R, called the reduced velocity, is used. V_R is defined as:

$$V_R = \frac{u}{f_i D}$$

where:

u = instantaneous flow velocity normal to the member axis [m/s]

f_i = the i'th natural frequency of the member [Hz]

D = member diameter [m].

(2)阻尼和临界阻力比ζ

一般单桩阻尼和临界阻力比ζ为0.02，导管架为0.01。

结构阻尼δ$_s$的相关规定如DNVGL-RP-C205中9.1.9节，其中对于暴露在风中的构件该值取0.0015；对于暴露在水中的构件，该值取为0.005~0.03（or 0.04）。

9.1.9 Structural damping

Structural damping is due to internal friction forces of the member material and depends on the strain level and associated deflection. For wind exposed steel members, the structural damping ratio ($\delta_s/2\pi$) may be taken as 0.0015, if no other information is available. For slender elements in water, the structural damping ratio at moderate deflection is typically ranging from 0.005 for pure steel pipes to 0.03 to 0.04 for flexible pipes.

Damping ratios for several structures and materials can be found in Blevins (1990).

(3)雷诺数

雷诺数可根据DNVGL-RP-C205中9.1.1节中的相关规定计算：

$$R_e = \frac{uD}{v}$$

9.1.1 General

Wind, current or any fluid flow past a structural component may cause unsteady flow patterns due to vortex shedding. This may lead to oscillations of slender elements normal to their longitudinal axis. Such vortex induced oscillations (VIO) should be investigated.

Important parameters governing vortex induced oscillations are:

— geometry (L/D)
— mass ratio ($m^* = m/(¼\pi\rho D^2)$)
— damping ratio (ζ)
— Reynolds number ($R_e = uD/\nu$)
— reduced velocity ($V_R = u/f_nD$)
— flow characteristics (flow profile, steady/oscillatory flow, turbulence intensity (σ_u/u) etc.).

where:

L	=	member length [m]
D	=	member diameter [m]
m	=	mass per unit length [kg/m]
ζ	=	ratio between damping and critical damping
ρ	=	fluid density [kg/m^3]
ν	=	fluid kinematic viscosity [m^2/s]
u	=	(mean) flow velocity [m/s]
f_n	=	natural frequency of the member [Hz]
σ_u	=	standard deviation of the flow velocity [m/s].

雷诺数的临界范围可依据DNVGL-RP-C205中9.1.2节中相关规定划分：

其中，层流、临界和超临界具有周期性，亚临界不具备周期性。

9.1.2 Reynolds number dependence

For rounded hydrodynamically smooth stationary members, the vortex shedding phenomenon is strongly dependent on Reynolds number for the flow, as given below.

$10^2 < R_e < 0.6 \times 10^6$	Periodic shedding
$0.6 \times 10^6 < R_e < 3 \times 10^6$	Wide-band random shedding
$3 \times 10^6 < R_e < 6 \times 10^6$	Narrow-band random shedding
$R_e > 6 \times 10^6$	Quasi-periodic shedding

For rough members and for smooth vibrating members, the vortex shedding shall be considered strongly periodic in the entire Reynolds number range.

此外，国内资料中（论文等）关于雷诺数临界范围的规定为：

雷诺数临界范围	
层流	0.1~100
亚临界	100~3×10^5
临界	3×10^5~6×10^6
超临界	6×10^6~

（4）斯特鲁哈尔数 St

斯特鲁哈尔数 St 随雷诺数的变化曲线可根据 DNVGL-RP-C205 中图 9-1 取值：

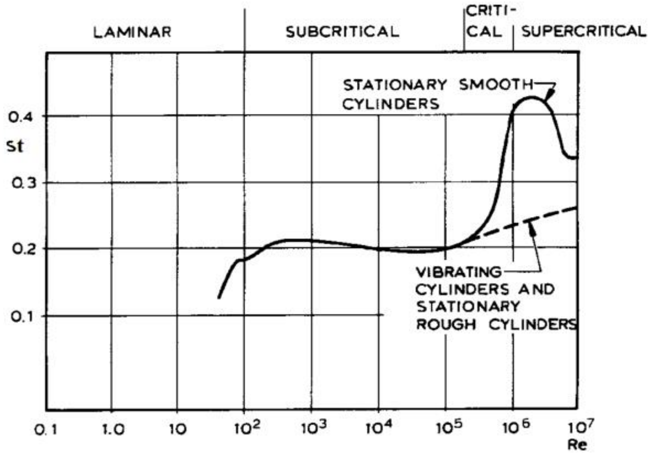


Figure 9-1 Strouhal number for a circular cylinder as a function of Reynolds number R_e

（5）稳定性系数 Ks

依据 DNVGL-RP-C205 中的 9.1.8 条的规定，结构稳定性系数 Ks 可根据下式计算。（此处的 m_e 为 1.1 中的 M_e）

9.1.8 Stability parameter

Another parameter controlling the motions is the stability parameter, K_S. It is also termed Scruton number. This parameter is proportional to the damping and inversely proportional to the total exciting vortex shedding

force. Hence the parameter is large when the damping is large or if the lock-in region on the member is small compared with the length of the pipe.
For uniform member diameter and uniform flow conditions over the member length the stability parameter is defined as:

$$K_S = \frac{2m_e\delta}{\rho D^2}$$

where:

ρ = mass density of surrounding medium (air/gas or liquid) [kg/m^3]

D = member diameter [m]

m_e = effective mass per unit length of the member, see [9.1.11] [kg/m]

δ = the logarithmic decrement (= $2\pi\zeta$)

ζ = the ratio between damping and critical damping

δ = $\delta_s + \delta_{other} + \delta_h$

δ_s = structural damping, see [9.1.9]

δ_{other} = soil damping or other damping (rubbing wear)

δ_h = hydrodynamic damping, see [9.1.10].

（6）流致结构频率

依据 DNVGL-RP-C205 中的 9.1.3 条的规定，流致结构频率f_s可根据下式计算。

9.1.3 Vortex shedding frequency

The vortex shedding frequency in steady flow or flow with K_C numbers greater than 40 may be calculated as follows:

$$f_s = St\frac{u}{D}$$

where:

f_s = vortex shedding frequency [Hz]

St = Strouhal number

u = fluid velocity normal to the member axis [m/s]

D = member diameter [m].

1.5.2 安全性判定

（1）线性激流（In-line）

依据 DNVGL-RP-C205 中的 9.6.3.2 条的规定，当满足下列条件时，会发生线性激流（In-line），尽量不发生线性激流（In-line），如若发生线性激流（In-line），原则上也可接受。

9.6.3.2 Pure in-line vortex shedding resonance (lock-in) may occur when:

$1.0 \le V_R \le 4.5$

$K_S \le 1.8$

（2）横向激流（Cross-flow）

依据 DNVGL-RP-C205 中的 9.6.4 条的规定，当满足下列条件时，会发生横向激流（Cross-flow），原则上不允许发生横向激流（Cross-flow）。

9.6.4 Cross flow VIV response model

9.6.4.1 Cross flow vortex shedding excitation may occur when:

$3 \le V_R \le 16$

for all Reynolds numbers, and the maximum response is normally found in the range $5 \le V_R \le 9$.

（3）频率共振判断

为保证结构不发生共振，结构固有频率和流致结构频率的比值应避开下式范围，即可保证不共振：

$$0.9 < \frac{f_1}{f_s} < 1.1$$

1.6 波浪主导的涡激振动危险性判断

1.6.1 模式判断

（1）参数 Kc

依据 DNVGL-RP-C205 中的 9.7.1.3 条的规定，参数 Kc 可根据下式计算。

9.7.1.3 The Keulegan-Carpenter number, K_C, is defined as:

$$K_c = v_m \frac{T}{D}$$

where:

v_m = maximum orbital velocity due to wave motion perpendicular to member axis for stationary cylinder. If the cylinder moves with the waves, it is the maximum relative velocity between the wave motion and the member.

T = wave period.

其中波浪速度 Vm 可由水质点运动轨道有益速度（非波速）Vs 替代，其中 Vs 的计算方法可根据 DNVGL-RP-C205 中的 9.7.1.4 计算。

9.7.1.4 In irregular flow the K_C number can be calculated by substituting v_m with the significant fluid velocity, v_s. Based on sea state parameters, the significant velocity in deep water can be estimated as:

$$v_s(z) = \frac{\pi H_s}{T_p} e^{k_p z}$$

where:

H_S = significant wave height

T_P = peak wave period

k_P = wave number corresponding to a wave with period T_P

z = vertical coordinate, positive upwards, where mean free surface is at z = 0.

当 Kc<40 时，采用模式一计算；当 Kc>40 时，采用模式二计算。

1.6.2 模式一安全性判定（Kc＜40）

约化速度V_R的计算可依据 DNVGL-RP-C205 中的 9.1.6 节，

9.1.6 Reduced velocity

For determination of the velocity ranges where the vortex shedding will be in resonance with an eigen frequency of the member, a parameter V_R, called the reduced velocity, is used. V_R is defined as:

$$V_R = \frac{u}{f_i D}$$

where:

u = instantaneous flow velocity normal to the member axis [m/s]

f_i = the i'th natural frequency of the member [Hz]

D = member diameter [m].

注意此处计算应取水质点运动轨道有益速度（非波速）Vs 替代水流速度（DNVGL-RP-C205 中的 9.7.1.4），计算方法如下：

9.7.1.4 In irregular flow the K_C number can be calculated by substituting v_m with the significant fluid velocity, v_s. Based on sea state parameters, the significant velocity in deep water can be estimated as:

$$v_s(z) = \frac{\pi H_s}{T_p} e^{k_p z}$$

where:

H_S = significant wave height

T_P = peak wave period

k_P = wave number corresponding to a wave with period T_P

z = vertical coordinate, positive upwards, where mean free surface is at z = 0.

依据 DNVGL-RP-C205 中的 9.7.2.1 条的规定，当 Kc<40 时，根据 Kc 值可取波浪频率的倍数 N。

9.7.2.1 For regular wave motion, a kind of resonance between waves and vortex shedding takes place. The vortex shedding frequency will be a multiple of the wave frequency. The number of vortex shedding oscillations per wave period, N, is in regular wave motion given by:

K_C	N
7 to 15	2
15 to 24	3
24 to 32	4
32 to 40	5

浪致涡脱频率（线性激流）的计算方法如下：

$$f_{wave} = N \times \frac{1}{T_p}$$

（1）线性激流（In-line）

依据 DNVGL-RP-C205 中的 9.7.5.1 条的规定，对于 Kc＜40 的波浪主导的涡激振动，当满足下列条件时，会发生线性激流（In-line），尽量不发生线性激流

（In-line），如若发生线性激流（In-line），原则上也可接受。

9.7.5.1 Locking-on conditions for K_C < 40:

In-line: $V_R > 1$

（2）横向激流（Cross-flow）

依据 DNVGL-RP-C205 中的 9.7.5.1 条的规定，对于 Kc＜40 的波浪主导的涡激振动，当满足下列条件时，会发生横向激流（Cross-flow），原则上不允许发生横向激流（Cross-flow）。

9.7.5.1 Locking-on conditions for K_C < 40:

Cross flow (with associated in-line motion): $3 < V_R < 9$

（3）频率共振判断

为保证结构不发生共振，结构固有频率和流致结构频率的比值应避开下式范围，即可保证不共振：

$$0.9 < \frac{f_1}{f_s} < 1.1$$

1.6.3 模式二安全性判定（Kc＞40）

约化速度的计算与 1.6.2 节相同。

依据 DNVGL-RP-C205 中的 9.1.3 条的规定，波致频率的计算如下所示：

9.1.3 Vortex shedding frequency

The vortex shedding frequency in steady flow or flow with K_C numbers greater than 40 may be calculated as follows:

$$f_s = St\frac{u}{D}$$

where:

f_s = vortex shedding frequency [Hz]

St = Strouhal number

u = fluid velocity normal to the member axis [m/s]

D = member diameter [m].

注意此处计算速度 u 应取水质点运动轨道有益速度（非波速）Vs（DNVGL-RP-C205 中的 9.7.1.4），计算方法如下：

9.7.1.4 In irregular flow the K_C number can be calculated by substituting v_m with the significant fluid velocity, v_S. Based on sea state parameters, the significant velocity in deep water can be estimated as:

$$v_s(z) = \frac{\pi H_s}{T_p} e^{k_p z}$$

where:

H_S = significant wave height

T_P = peak wave period

k_P = wave number corresponding to a wave with period T_P

z = vertical coordinate, positive upwards, where mean free surface is at z = 0.

（1）线性激流（In-line）

依据 DNVGL-RP-C205 中的 9.7.3.3 条的规定，对于 Kc＞40 的波浪主导的涡激振动，当满足下列条件时，会发生线性激流（In-line），尽量不发生线性激流（In-line），如若发生线性激流（In-line），原则上也可接受。

9.7.3.3 Resonance vibrations due to vortex shedding (locking-on) may occur as follows for $K_C > 40$:

In-line excitations:

$1 < V_R < 3.5$

$K_S < 1.8$

（2）横向激流（Cross-flow）

依据 DNVGL-RP-C205 中的 9.7.5.1 条的规定，对于 Kc＞40 的波浪主导的涡激振动，当满足下列条件时，会发生横向激流（Cross-flow），原则上不允许发生横向激流（Cross-flow）。

9.7.3.3 Resonance vibrations due to vortex shedding (locking-on) may occur as follows for $K_C > 40$:

Cross flow:

$3 < V_R < 9$

（3）频率共振判断

为保证结构不发生共振，结构固有频率和流致结构频率的比值应避开下式范围，即可保证不共振：

$$0.9 < \frac{f_1}{f_s} < 1.1$$

1.7 拖拽力系数 C_d 的修正

1.7.1 拖拽力系数的相关规定

依据 APIRP2A-LRFD-2019 中的 9.5.2.3 节中的相关规定，拖拽力系数 C_d 在粗糙时可取 1.05，基于安全考虑本计算中 C_{d0} 系数取 1.05。

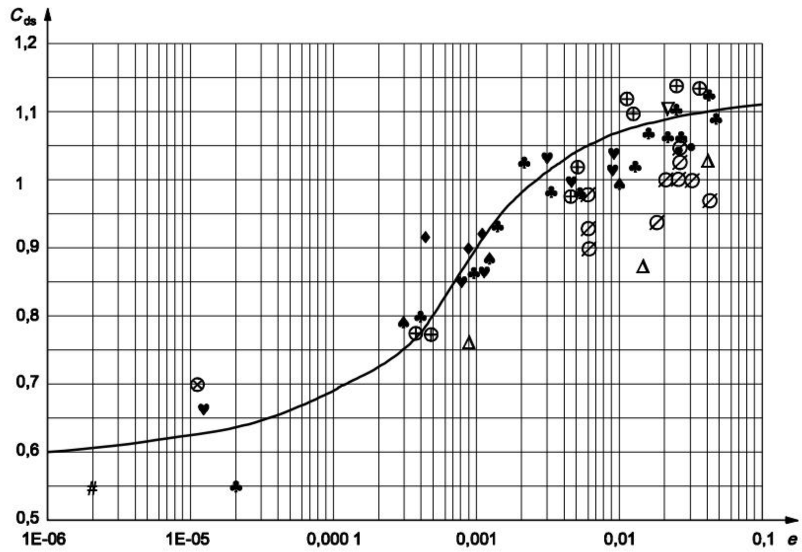
9.5.2.3 Drag and Inertia Coefficients

For typical design situations, global hydrodynamic load/action on a structure can be calculated using Morison equation, with the values of the hydrodynamic coefficients for unshielded circular cylinders given in Table 9.5-1.

Table 9.5-1—Typical Values of Hydrodynamic Coefficients

Surface of Component	C_d	C_m
Smooth	0.65	1.6
Rough	1.05	1.2

关于 C_d 与粗糙度的关系在 APIRP2A-LRFD-2019 中的表 A.9.5.2 中给出，作为参考。



Key

e relative roughness
C_{ds} steady-flow drag coefficient at post-critical Reynolds numbers
Jones (1989)
∆ Blumberg (1961)
• Wolfram (1985)
♣ Miller (1976)
♦ Szechenyl (1975)
♥ Achenbach (1971, 1981)
♠ Wang (1986)
⊗ Roshco (1961)
⊕ Norton (1983)
∅ Nath (1987)
∇ Rodenbusch (1983)

Figure A.9.5-2—Dependence of Steady-flow Drag Coefficient on Relative Surface Roughness

1.7.2 线性激流（In-line）的 C_d 修正

依据 DNVGL-RP-C205 2019 中的 9.6.3.6 节的相关规定，图 9-5 展示了振幅与直径比和稳定性参数 K_S 的相对关系图。

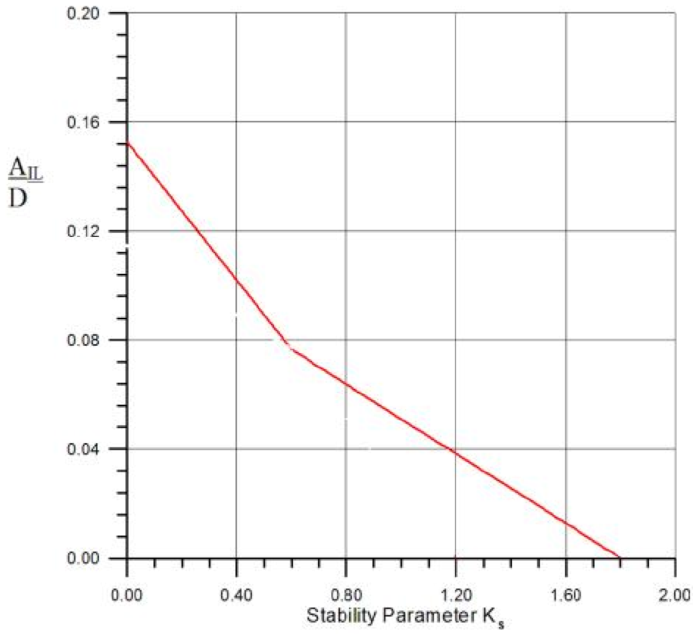


Figure 9-5 Amplitude of in-line motion as a function of K_s (CIRIA, 1977)

Ks 的计算与 1.3.1 节中一致。

通过前面计算中求得的 Ks 可查出 A/D 的值，作为输入项，输入到表格中。

修正后的拖拽力系数计算：

依据 DNVGL-RP-C205 中的 9.2.2.3 条的规定，对于波浪主导的 C_d 系数修正可通过下式进行：

9.2.2.3 The drag amplification in wave dominated flows is smaller than in pure current conditions. Drag amplification in waves may be taken as (Jacobsen et.al., 1985):

$C_D = C_{Do}\left[1 + \frac{A}{D}\right]$　　波浪主导

1.7.3 横向激流（Cross-flow）的 C_d 修正

依据 DNVGL-RP-C205 2019 中的 9.5.3.3 节的相关规定，图 9-4 展示了振幅与直径比和稳定性参数 Ks 的相对关系图。

9.5.3.3 For strongly turbulent wind flow, the given amplitudes are conservative.

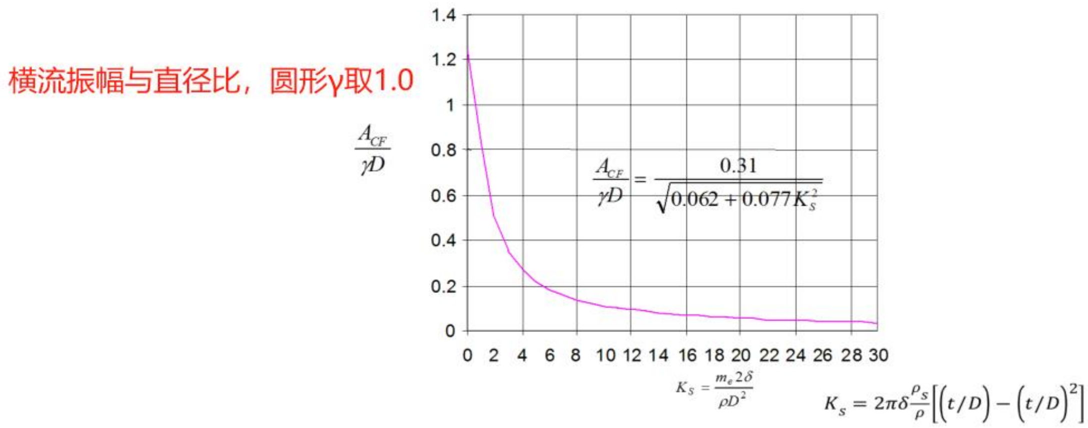


Figure 9-4 Amplitude of cross flow motions as function of K_S (Sarpkaya, 1979)

Ks 的计算与 1.3.1 节中一致。

通过前面计算中求得的 Ks 可查出 A/D 的值，作为输入项，输入到表格中。

修正后的拖拽力系数计算：

依据 DNVGL-RP-C205 中的 9.2.2.3 条的规定，对于波浪主导的 C_d 系数修正可通过下式进行：

9.2.2.3 The drag amplification in wave dominated flows is smaller than in pure current conditions. Drag amplification in waves may be taken as (Jacobsen et.al., 1985):

$C_D = C_{Do}\left[1 + \frac{A}{D}\right]$　波浪主导

2.风致涡激振动

2.1 输入参数及参数计算

（1）基本参数

基本参数应包含：钢管直径 D、钢管厚度 t、杆件长度 L、风速度 u、水深 d、空气的粘滞系数 υ、钢材弹性模量 E、截面惯性矩 I、钢材密度 ρ $_s$、风密度 ρ 。

（2）杆件两端固定类型参数 An

杆件两端固定类型参数 An 与 1.1 节中取值相同，规定如下：

杆件两端固定类型参数 An 可根据下表进行取值：

表 1-1 杆件两端固定类型参数 An

杆件两端固定类型	A_n 取值
固定-自由	3.52
铰接-铰接	9.87
固定-铰接	15.40
固定-固定	22.40

（表格来源于论文《大型深水导管架建造工况条件下的杆件涡激振动评估_卫旭敏》）

(3)阻尼和临界阻力比ξ

暴露在风中的构件的阻尼和临界阻力比ξ值取 0.0015。

结构阻尼 δ_s的相关规定如 DNVGL-RP-C205 中 9.1.9 节，其中对于暴露在风中的构件该值取 0.0015；对于暴露在水中的构件，该值取为 0.005~0.03（or 0.04）。

9.1.9 Structural damping

Structural damping is due to internal friction forces of the member material and depends on the strain level and associated deflection. For wind exposed steel members, the structural damping ratio ($\delta_s/2\pi$) may be taken as 0.0015, if no other information is available. For slender elements in water, the structural damping ratio at moderate deflection is typically ranging from 0.005 for pure steel pipes to 0.03 to 0.04 for flexible pipes.

Damping ratios for several structures and materials can be found in Blevins (1990).

(4)雷诺数

雷诺数可根据 DNVGL-RP-C205 中 9.1.1 节中的相关规定计算：

$$R_e = \frac{uD}{v}$$

9.1.1 General

Wind, current or any fluid flow past a structural component may cause unsteady flow patterns due to vortex shedding. This may lead to oscillations of slender elements normal to their longitudinal axis. Such vortex induced oscillations (VIO) should be investigated.

Important parameters governing vortex induced oscillations are:

— geometry (L/D)
— mass ratio ($m^* = m/(¼\pi\rho D^2)$)
— damping ratio (ζ)
— Reynolds number ($R_e = uD/\nu$)
— reduced velocity ($V_R = u/f_nD$)
— flow characteristics (flow profile, steady/oscillatory flow, turbulence intensity (σ_u/u) etc.).

where:

L = member length [m]

D = member diameter [m]

m = mass per unit length [kg/m]

ζ = ratio between damping and critical damping

ρ = fluid density [kg/m^3]

ν = fluid kinematic viscosity [m^2/s]

u = (mean) flow velocity [m/s]

f_n = natural frequency of the member [Hz]

σ_u = standard deviation of the flow velocity [m/s].

雷诺数的临界范围可依据 DNVGL-RP-C205 中 9.1.2 节中相关规定划分：

其中，层流、临界和超临界具有周期性，亚临界不具备周期性。

雷诺数临界范围	
层流	0.1~100
亚临界	100~3xE05
临界	3xE05~1xE06
超临界	1xE06~

9.1.2 Reynolds number dependence

For rounded hydrodynamically smooth stationary members, the vortex shedding phenomenon is strongly dependent on Reynolds number for the flow, as given below.

$10^2 < R_e < 0.6 \times 10^6$	Periodic shedding
$0.6 \times 10^6 < R_e < 3 \times 10^6$	Wide-band random shedding
$3 \times 10^6 < R_e < 6 \times 10^6$	Narrow-band random shedding
$R_e > 6 \times 10^6$	Quasi-periodic shedding

For rough members and for smooth vibrating members, the vortex shedding shall be considered strongly periodic in the entire Reynolds number range.

（5）斯特鲁哈尔数 St

斯特鲁哈尔数 St 随雷诺数的变化曲线可根据 DNVGL-RP-C205 中图 9-1 取值：

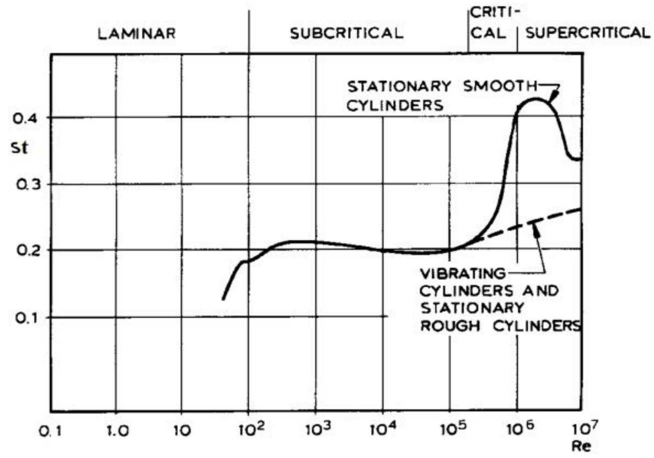


Figure 9-1 Strouhal number for a circular cylinder as a function of Reynolds number R_e

注意：风致涡激振动计算时，St 取值为 0.2。

（6）单位有效质量 Me

无论对于单桩还是导管架，结构内部的气体可忽略不计，因此单位长度结构内部的空气质量为 0，即 M_{air}=0。

有效的结构质量为单位长度的钢材质量 Ms，计算方法如下：

$$M_s = \pi\rho_s Dt$$

基于以上计算，单位有效质量的计算方法为：

$$M_e = M_s$$

(7)约化速度（风折算速度）V_R

约化速度V_R的计算可依据 DNVGL-RP-C205 中的 9.1.6 节：

9.1.6 Reduced velocity

For determination of the velocity ranges where the vortex shedding will be in resonance with an eigen frequency of the member, a parameter V_R, called the reduced velocity, is used. V_R is defined as:

$$V_R = \frac{u}{f_i D}$$

where:

u = instantaneous flow velocity normal to the member axis [m/s]

f_i = the i'th natural frequency of the member [Hz]

D = member diameter [m].

2.2 构件的一阶自振频率

注意：此处只能用用于构件（杆件）的一阶自振频率计算，对于单桩整体结构不使用此处公式计算频率，可通过 SACS 进行计算。

波浪波长 L 计算方法如下：

$$L = \frac{2\pi}{k}$$

波浪参数 1 为 kd；

波浪参数 2 为 thkd 为：

$$\mathrm{thkd} = \frac{e^{kd} - e^{-kd}}{e^{kd} + e^{-kd}}$$

修正波长 L’为：

$$L^{'} = thkd \times L$$

一阶自振频率f_1为：

$$f_1 = \frac{A_n}{\pi}\sqrt{\frac{EI}{M_e L^4}}$$

2.3 风致涡激振动

2.3.1 线性激流（In-line）

依据 DNVGL-RP-C205 中的 9.5.2 节的相关规定，线性激流（In-line）的涡激振动可根据 9.5.2.1 中相关规定判断。

注意：本技术规程依据文献等信息认为风致涡激振动可允许线性激流（In-line）发生。因此该条不考虑，即不计算风致涡激振动的线性激流（In-line）。

9.5.2 In-line vibrations

9.5.2.1 In-line vibrations may occur when:

$$\frac{0.3}{St} < V_R < \frac{0.65}{St}$$

In-line vibrations may only occur for small stability parameters, i.e. K_s < 2. The stability parameter is defined in [9.1.8].

2.3.2 横向激流（Cross-flow）

（1）临界风速判定

依据 DNVGL-RP-C205 中的 9.5.3 节的相关规定，横向激流（Cross-flow）的涡激振动应满足 9.5.3 中相关规定。

9.5.3 Cross flow vibrations

9.5.3.1 Cross flow vibrations may occur when:

$$\frac{0.8}{St} < V_R < \frac{1.6}{St}$$

where:

V_R = $U_w / (f_n D)$ is the reduced velocity [-]
St = Strouhal number [-]
U_w = wind velocity [m/s]
f_n = natural frequency of member [1/s]
D = characteristic cross-sectional dimension [m].

基于 DNVGL-RP-C205 中 9.5.4.6 中的相关规定（根据 DNVGL-RP-C205 中 9.5.3 节和约化速度的计算公式推到而来），横向涡激振动的临界下限风速可根据下式计算：

9.5.4.6 The lower limit for wind velocity inducing cross-flow vibrations of the member is given by the reduced velocity, defined in [9.5.3],

$$V_R^* = \frac{0.8}{St}$$

or equivalently in terms of the limiting wind velocity

$$U_w^* = 0.8\frac{Df_n}{St}$$

where:

St = Strouhal number
f_n = natural frequency of member [1/s]
D = characteristic cross-sectional dimension [m].

Guidance note:
The St may be taken as 0.2 for circular cross sections and as 0.12 for rectangular cross-sections. Strouhal numbers for other beam profiles are given in Table 9-2.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

依据 DNVGL-RP-C205 中 9.5.4.7 节中相关规定。若高度 z 处一年重现期一分钟的平均风速$U_{1year，1min} < U_w^*$，则认为不会发生横向激流（Cross-flow）涡激振动，无需进行下面的计算。

9.5.4.7 Members of a space frame structure can be assumed to be without risk to wind induced VIV if
$U_{1year,\ 1\mathrm{min}}(z) < U_w^*$
where:
$U_{1year,\ 1\mathrm{min}}(z)$ = 1 minute mean speed at the location z of the member with a return period of 1 year.

（2）杆件稳定系数 Ks 和临界雷诺数 Re*判定

依据 DNVGL-RP-C205 中 9.5.4.8 节中相关规定。若上述风速条件不满足,但满足下列条件,则 仍可认为不会发生风涡激振动:

9.5.4.8 When the 1-year wind velocity defined above exceeds U_w^*, the member can still be assumed to be without risk to VIV if the following criteria in terms of Reynolds number and stability parameter K_s are fulfilled:

$$K_s \cdot R_e^* \geq 7.5 \cdot 10^6 \text{ for } 3 \cdot 10^5 < R_e^* < 5 \cdot 10^5$$

$$K_s \geq 15 \qquad \text{for } R_e^* > 5 \cdot 10^5$$

where:

$$R_e^* = \frac{U_w^* D}{\nu}$$

is the Reynolds number at the wind velocity U_w^*.

Guidance note:

The criteria above are based on the fact that the oscillating lift force on the member is drastically reduced in the critical flow range occurring at Reynolds number around $3 \cdot 10^5$ and the fact that the amplitude of the transverse oscillations is limited when the stability parameter is large.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

$$\text{在 } 3\times10^5 < Re^* < 5\times10^5 \text{ 时，} K_s \times Re^* \geqslant 7.5\times10^6 \tag{6}$$

$$\text{在 } Re^* > 5\times10^5 \text{ 时，} K_s \geqslant 15 \tag{7}$$

杆件稳定系数 Ks 可根据下式计算：

Guidance note:

For steel tubular members the stability parameter is given by:

$$K_s = 2\pi\delta\frac{\rho_s}{\rho}\left[\left(t/D\right) - \left(t/D\right)^2\right]$$

where:

ρ_s = density of steel [kg/m^3]

ρ = density of air (1.25 kg/m^3 at 10°C) [kg/m^3]

δ = structural damping $\delta = 2\pi\zeta$ where $\zeta = 0.0015$

D = member diameter [m]

t = thickness [m].

在表格中表现为：满足标红部分中任意一条，即可认为安全。

在 $3\times10^5 < Re^* < 5\times10^5$ 时，$K_s \times Re^* \geqslant 7.5\times10^6$ (6)		不安全	
在 $Re^* > 5\times10^5$ 时，$K_s \geqslant 15$		不安全	
判断条件二判断结果	满足上两行结果任意一个即安全	不安全	