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INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

GATE EDGE SUCTION AS A CAUSE OF SELF-EXCITING VERTICAL VIBRATIONS

(Subject C.c)

by P.A. Kolkman and A. Vrijer

Head and Project Engineer of the Locks,
Weirs and Sluices Branch of the Delft
Hydraulics Laboratory, Netherlands

Summary

A theory on self-exciting vertical vibrations is presented which comprises the following elements:
- Gate raise variations induce discharge fluctuations,
- Discharge fluctuations and flow inertia cause local pressure difference variations across the gate opening,
- Local pressure difference variations result in variations of the force exercised by the water on the gate; they also affect the discharge fluctuations.

From this theory follows that self-excitation occurs in gates when suction forces are generated in the gate opening. Even when flow separation occurs at a stable point at the upstream side of the gate edge self-excitation can occur. The Strouhal Number (S) lies in a critical range between 0 and 0.1.

The theory has been tested on a gate with a lower edge having a right-angled lip. Self-exciting vertical vibrations did appear at low S values. These vibrations were recognizable by a strictly exponential increase. The critical S range turned out to be between 0.012 and 0.2; i.e. somewhat higher than predicted by theory. Maximum self-excitation was of an order that accorded with theory, but occurred in a smaller range of S values.

Sommaire

Il est présentée une théorie concernant les vibrations verticales auto-excitantes des vannes. Cette théorie englobe les phénomènes suivants:
- Des variations de la grandeur d'ouverture mènent à des fluctuations du débit.
- Les variations du débit et l'inertie de l'ecoulement causent des variations des différences de pression locales de part et d'autre de la vanne.
- Les variations des différences de pression locales provoquent des variations des forces de l'eau agissant sur la vanne; d'autre part, ces variations de pression sont également à l'origine de fluctuations de débit.

De cette théorie, il ressort que s'il se produit des efforts de succion dans le jour de la vanne, des vibrations s'amorcent. Même si le courant se détache à un endroit fixe en amont de la vanne, celle-ci peut se mettre à vibrer. Le nombre de Strouhal (S) se situe dans une zone critique entre 0 et 0,1.
La théorie a été vérifiée à l'aide d'expériences, notamment sur une vanne à lèvre d'équerre au bord inférieur. Aux valeurs S basses, des vibrations verticales s'amorçaient. Ces vibrations pouvaient s'identifier par une croisance purement exponentielle. La zone critique de S s'est avérée se situer entre 0,012 et 0,2; elle est donc quelque peu supérieure à celle que laisait prévoir la théorie. L'amplitude maximum des vibrations auto-excitantes se situait dans un ordre de grandeur correspondant à l'ordre théorique, mais elle se produisait dans une zone plus étroite du nombre S.

1. Introduction

With some frequency, publications have appeared on the prevention of vibrations in flow-regulating gates, which vibrations are most probably induced by flow separation at the lower gate edge. The authors of this paper were also acquainted with this phenomenon from their own experience with models and also with prototypes. Sharp gate edges turn out to be efficient in suppressing the phenomenon, except when the gate raise is of the same order as the edge thickness. Investigators have directed their attention in particular to the frequency range in which turbulent pressure variations occur without vibration of the gate (see Naudascher [1],[2] and Hardwick [3]). The mechanism of feedback of vibrations is little investigated: to be mentioned are Harding [4], Abelev [5] and Thomann [6]. In his thesis [7], the first author of this paper has made an attempt at a mathematical description of the feedback mechanism of vertically induced vibrations. His theory gives some indications that can be useful in the design of gates (see Par. 6).

Model investigations have been carried out to test the various elements of the theory, especially those concerning design aspects. These investigations form part of a commission of the Dutch Ministry of Public Works, aimed at improved design techniques for gates.

2. Underlying Theory

Calculations are based on a vertically vibrating gate (see Figure 1). The thin right-angled lip was provided to eliminate the influence of the added mass of water, which now only causes a local flow pattern around the edge of the lip and produces little current in the upstream and downstream water.
In the calculations, it is assumed that all velocity fluctuations due to discharge fluctuations and to added mass effects produce a potential flow and that the related velocity and pressure variations in each point can be superposed on the stationary values. This assumption holds true for higher S values. This follows from comparative analysis of the Navier-Stokes equation when vibrations occur in stagnant and in flowing water ([7], Chapter IV).
The in-phase and out-of-phase forces at stationary gate vibrations are calculated in terms of (spring) rigidity and damping. In dealing with the out-of-phase forces, the following assumptions were made:
- the effect of surface waves is negligible;
- the discharge coefficient is constant;

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[1] Naudascher, E., "From Flow Instability to Flow-Induced Excitation", Proc. ASCE, Journ. Hydr. Div. HY4, July 1967, paper 5336.
[2] Martin,W., Naudascher,E., Padmanabhan,M.,"Fluid Dynamic Excitation involving Flow Instability", Proc. ASCE, Journ. Hydr. Div. HY6, June 1975, paper 11361.
[3] Hardwick, J.D., "Flow-Induced Vibration of Vertical Lift Gate", Proc. ASCE, Journ. Hydr. Div. HY5, May 1974, paper 10546.
[4] Harding, D.A., "The Stability of a Relief Valve connected to a Long Pipe", 10th IAHR Congress, London 1963, paper 3.18.
[5] Abelev, A.S., Dolnikov, L.L., "Experimental Investigations of Self-Excited Vibrations of Submerged Vertical-Lift Hydraulic Gates", IUTAM/IAHR Symp. on Flow-Induced Vibrations, Karlsruhe 1972 (Springer Verlag 1974).
[6] Thomann, H., " Oscillations of a simple Valve connected to a Pipe", Journ. of Appl. Math. and Physics (ZAMP), Vol. 27, 1976, pp. 23-40.
[7] Kolkman, P.A., "Flow-Induced Gate Vibrations", Delft Hydraulics Lab. Publ. 164, June 1976.

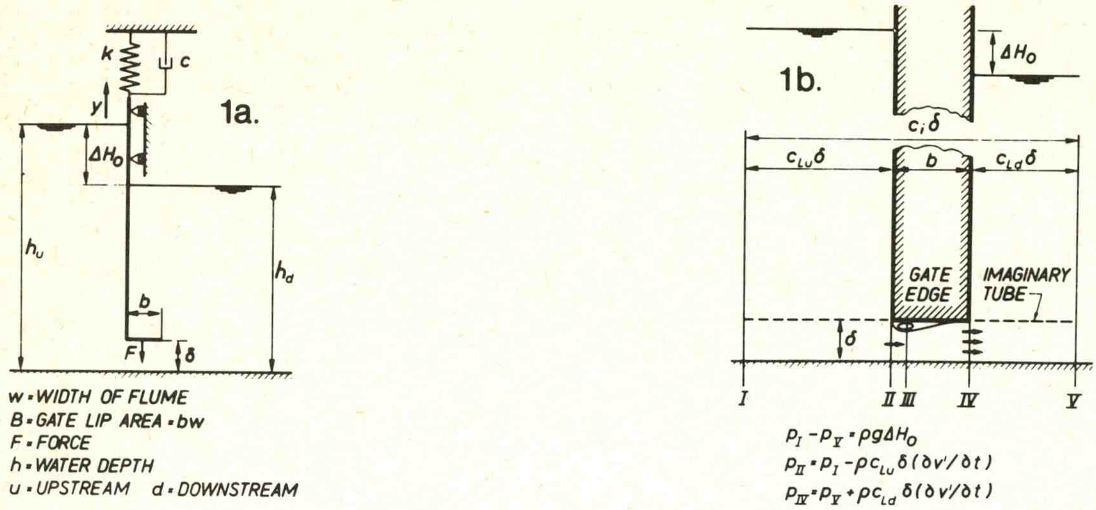

Fig. 1 Definitions and calculation scheme
Définitions et plan de calcul

- suction forces during vibration are proportional to the head difference at each moment; and
- changes of the flow pattern due to discharge fluctuations are calculated as if in a gate opening of constant width the velocity profile is rectangular.

When a gate is vibrating, its discharge will fluctuate:

$$\hat{Q} = \mu w \hat{\delta} \sqrt{2g\Delta\hat{H}} \tag{1}$$

$\hat{}$ designates a non-stationary magnitude,
ΔH is the local head difference across the gate opening.
If calculations are started with a stationary vibration of small amplitude, the discharge fluctuations and head difference variations will be small compared with average values and it may be assumed that they are harmonic.

We define $\hat{Q} = Q_o + Q'$, $\Delta\hat{H} = \Delta H_o + \Delta H'$ and $\delta = \delta_o + y$ and we consider only the fluctuating part. Equation (1) now becomes:

$$Q' = \frac{\partial\hat{Q}}{\partial\delta} d\delta + \frac{\partial\hat{Q}}{\partial\Delta H} d\Delta H$$

$$\approx \mu w \sqrt{2g\Delta H_o} \,.\, y + \frac{\mu w \delta_o}{2} \sqrt{\frac{2g}{\Delta H_o}} \,.\, \Delta H' \tag{1a}$$

In the downstream water there arise pressure gradients proportional to $\partial Q/\partial t$, which are depicted in Figure 1b in a diagram of a gate opening extended on both sides by imaginary tubes of a length $c_{Lu}\delta$ and $c_{Ld}\delta$. Inertia over the total length $c_i\delta$ of the resulting flow channel causes a difference from the local head difference ΔH_o across the opening.

$$(\Delta\hat{H} - \Delta H_o)\,\rho g = -c_i \delta \rho d\hat{V}/dt \tag{2}$$

wherein $c_i = c_{Lu} + c_{Ld} + b/\delta$

As $d\hat{V}/dt = dV'/dt$ and $Q' = w\delta V'$,

$$\Delta H' = -c_i(\partial Q/\partial t)/gw \tag{2a}$$

The suction force is proposed to be proportional to $\Delta\hat{H}$:

$$\hat{F} = c_F \rho g B \Delta\hat{H} \tag{3}$$

or

$$F' = c_F \rho g B \Delta H' \tag{3a}$$

Using the linear Equations (1a), (2a) and (3a), the in-phase and out-of-phase forces can be calculated. To this end we introduce $F' = F'e^{i\omega t}$, $y = ye^{i\omega t}$, etc. and divide all terms by $e^{i\omega t}$. Equations (1a) and (3a) do not change, but (2a) becomes:

$$\Delta H' = -i\omega c_i \cdot Q'/gw \tag{2b}$$

Elimination of $\Delta H'$ and Q' from the three equations leads to the equation:

$$F' = \frac{-i\omega c_F \rho B c_i}{w}\left(\mu w \sqrt{2g\Delta H_o} \cdot y + \frac{\mu w \delta_o g}{\sqrt{2g\Delta H_o}} \cdot \frac{F'}{c_F \rho g B}\right) \tag{4}$$

When F' is expressed in y, the resulting equation can be simplified by introducing the Strouhal Number $S = \omega\delta/2\pi\sqrt{2g\Delta H_o}$ and by subsequently multiplying denominator and numerator by the conjugated complex value of the denominator, and we get:

$$\frac{F'}{y} = \frac{-(1 - i2\pi S\mu c_i)\, i\omega c_F \rho B c_i \mu \sqrt{2g\Delta H_o}}{1 + (2\pi S\mu c_i)^2} \tag{5}$$

Expressed in hydrodynamic (spring) rigidity k_w and water damping c_w, the force is:

$$F' = k_w y + c_w\, dy/dt,$$

or

$$\frac{F'}{y} = k_w + ic_w\omega \tag{6}$$

The negative water damping, which causes self-excitation, is found by dividing the imaginary part of Equation (5) by $(-i\omega)$. We now introduce the coefficient of self-excitation c_{SE}, which is:

$$c_{SE} = (-c_w)/c_F \rho B \sqrt{2g\Delta H_o} = \mu c_i/(1 + (2\pi S\mu c_i)^2 \tag{7}$$

Likewise, negative hydrodynamic rigidity can be derived. It has its maximum at high values of S and can be calculated by assuming that Q is constant: If y increases, $\Delta H'$ decreases and this, according to Equation (3a) leads to a decreasing suction force. Equation (7) is illustrated in Figure 7 for a few values of μc_i. Quantification of self-excitation, or negative damping, requires more knowledge about the coefficients c_i and c_F.

3. Coefficients

The part c_s of force coefficient c_F represents the reduced pressure or vertical suction generated, e.g. in Section III of Figure 1b, in the case of flow release and reattachment (approximately when $\delta/b < 0.65$). At small gate raises, the width of the zone of reduced pressure will be proportional to the gate raise δ.

At greater gate raises than about $\delta = 0.65$ b, reattachment will not occur so that no suction is exercised during stationary flow conditions, i.e. $c_s = 0$. For rectangular gate edge sections it has been calculated that c_s has a maximum value of 0.5. When $\delta/b < 0.65$, c_s is proportional to δ.
Other forces are created by flow inertia in the downstream water. In Figure 1b they are symbolized by an imaginary tube of a length $c_{Ld}\delta$. The total dynamic pressure operative under the gate edge is:

$$p'_{IV}/\rho g - c_s \Delta H' \qquad (8)$$

p is dependent on h_d, but for p'_{IV} flow inertia has to accounted for in the same way as in Equation (2a):

$$p'_{IV}/\rho g = c_{Ld}\ (\partial Q'/dt)/gw \qquad (9)$$

(Minus-signs in the equations arise from the convention that suction forces are positive.)
From Equations (2a) and (9) follows:

$$p'_{IV}/\rho g = (c_{Ld}/c_i)\ \Delta H' \qquad (10)$$

Now the total suction force on the gate edge is obtained from Equations (3a) and (8):

$$F' = c_F \rho g B \Delta H' = (c_s + c_{Ld}/c_i)\ \rho g B \Delta H' \qquad (11)$$

or

$$c_F = c_s + c_{Ld}/c_i \qquad (12)$$

If the gate edge is provided with a right-angled lip, the pressure p'_{IV} will not only be operative below, but to a lesser extent also above the lip, which changes Equation (12) to:

$$c_F = c_s + \theta c_{Ld}/c_i \qquad (13)$$

Pressure measurements to verify the calculated values of c_s have been made in a separate constant-flow model. The values of μ were also determined: for $\delta/b < 0.65$, μ was about 0.63; for greater gate raises, it was about 1. (Occasionally, values above 1 were measured.)
The values of c_{Ld} and c_{Lu} were derived from potential flow of the type generated by a horizontally vibrating vertical plate of a height equal to that of the gate opening (see [7] for particulars).
Investigations by means of an electrical analog model showed that a right-angled lip produces no substantial deviations from schematized calculations. Schematization and the results of calculations are shown in Figure 2. The upstream and downstream values of c_L (c_{Lu} and c_{Ld}) are different, because depths h_u and h_d are different. The analog model was also used to determine some values of θ for different values of δ/b and h_d/δ (see Figure 3).
We will not go into the application of the analog model to the determination of c_L, θ and the added mass of water. For free-surface conditions, the basic rules have already been formulated by Zienkievicz and Nath [8] and more can be found in [7].

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[8] Zienkiewicz, O.C., Nath, B., "Analogue Procedure for Determination of Virtual Mass", Proc. ASCE, Journ. of Hydr. Div. HY5, Sept. 1964, pp. 69-81.

4. The Model

The gate model was a vertical, flat aluminium plate with a right-angled lip at its lower edge. The plate was rigidified by means of vertical ribs and extended well above the water, where the gate was stabilized by means of long, horizontal tension wires, so that only vertical vibration was allowed. Accuracy of measurement was unfavourably influenced by some bending of the gate under head differences. This resulted in additional water damping. An attempt was made to suppress this effect by tautening extra wires near the edge. The gate was suspended from a spring.
The channel width was 0.5 m, the lip width b was 0.01 m and the gate raise was varied between 0.0067 and 0.07 m. Water depth (the average of h_u and h_d) was varied between 0.1 and 0.4 m.
The gate weight varied between 4 and 5 kg, and the spring rigidity was varied between 1100 and 13000 N/m (resulting in a frequency variation between 2.4 and 8.8 c/s). Measured were the spring force, the exponential increase of the amplitude, and the equilibrium amplitude. Measurement of the equilibrium amplitude was not always possible, because of the mechanical limits to free vibration; sometimes the gate even hit the bottom.

5. Measurements

Results are given for a gate raise of 0.015 m (i.e. $\delta/b = 1.5$). For gate raises $\delta/b = 0.67$, 1.0 and 7.0, similar results were obtained. For $\delta/b = 0.5$ nearly no self-excitation was found. In nearly all cases, vibrations started purely exponential.
Figure 4 shows the maximum measured values of negative water damping coefficients ($-c_{w}/\rho B\sqrt{2g\Delta H_o}$) as functions of the Strouhal Number S. Though measurements with varying spring rigidity, head difference and water depth showed good coincidence, some times a strongly downward deviation was found.
Figure 5 shows the maximum equilibrium amplitude values found. In these measurements, deviations were fairly small; this indicates that non-linear factors limiting amplitude increase are tied with y/δ values.
In Figure 6, the range of δ/b values investigated is shown. Within this range, the critical Strouhal Numbers are to be found.
Figure 7 shows the results of an attempt to derive the self-excitation coefficient c_{SE} (Equation (7)) from the negative water damping values, using coefficients obtained from (incomplete) measurements under stationary flow conditions and from the electrical analog model.
The results indicate that our theory gives a good representation of the maximum excitation values. This was also for δ/b values of 0.67 and 1; for $\delta/b = 7$ no value of θ was available. The influence of μc_i is also well represented qualitatively. The theory indicates that when S decreases byond a certain value, c_{SE} remains constant. The measurements indicated, however, that c_{SE} decreases again. Also, the critical values of S are a factor 2 to 4 higher than indicated by theory. (S increases at increasing values of δ/b. See Figure 6.)

Remark: The assumption that discharge fluctations induce pressures in accordance with the potential theory, is only valid for high values of S. So it might be possible that in the range of low S values c_L, and also c_{SE}, decreases strongly.

6. Conclusions

Though our theory was not entirely confirmed by the experiments, it was essentially vindicated, particularly in those aspects that are of interest in gate design. It leads to the conclusion that:
- Gate shapes which induce suction forces in the gate opening are in principle susceptible to vibration, even with stable flow attachment and/or separation.
- Inertia effects in upstream and downstream water, together with suction forces,

are responsible for unstable vibrations.

- Gates can also be subject to vibration when the flow is released at a fixed point at the upstream side of the gate edge.
- The critical range of S lies between 0.01 and 0.2. Especially for low gate raises, the values of S found both theoretically and experimentally are considerably lower than the values found in turbulence investigations of gates, in which the critical value of S was always above 0.2.

Symbols

Time dependent variabeles: $\hat{\delta}$, $\Delta\hat{H}$, $\hat{Q}$, of which δ_o, ΔH_o, Q_o are the stationary components and y, H' and Q' are the non-stationary components.

b	lip width	(m)	ΔH	local head over gate	(m)
B	lip area	(m^2)	k	spring rigidity	(kgs^{-2})
c	mechanical damper	(kgs^{-1})	k_w	hydrodynamic rigidity	(kgs^{-2})
c_F	force coefficient		m	gate mass	(kg)
c_i	inertia coefficient		p	pressure	($kgm^{-1}s^{-2}$)
c_{Ld}	downstream length coeeficient		Q	discharge	(m^3s^{-1})
c_{Lu}	upstream length coefficient		S	Strouhal Number = $\omega\delta_o/2\pi\sqrt{2g\Delta H}$	
c_s	suction force coefficient		t	time	(s)
c_{SE}	self-excitation coefficient		w	gate width	(m)
c_w	water damping	(kgs^{-1})	y	gate displacement	(m)
F	excitation force	($kgms^{-2}$)	Y_o	vibration amplitude	(m)
g	gravity acceleration	(ms^{-2})	δ	gate raise	(m)
h_d	downstream depth	(m)	μ	discharge coefficient	
h_u	upstream depth	(m)	ω	angular frequency	(s^{-1})

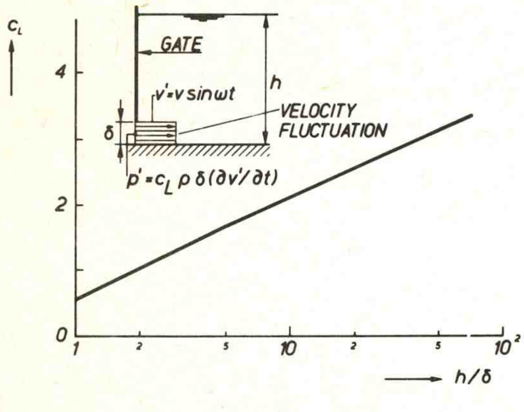

Fig. 2 c_L coefficient. Le coefficient c_L

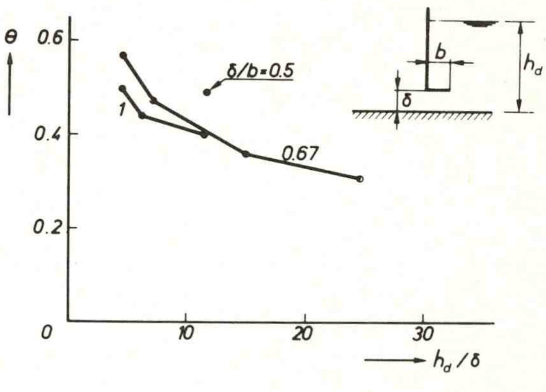

Fig. 3 θ values of right angled lip
Valeurs de θ de la lèvre d'équerre

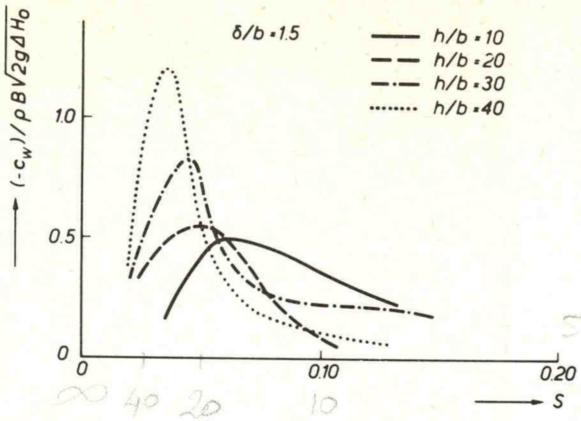

Fig. 4 Maximum negative hydrodynamic damping
Maximum de l'amortissement hydrodynamique négatif

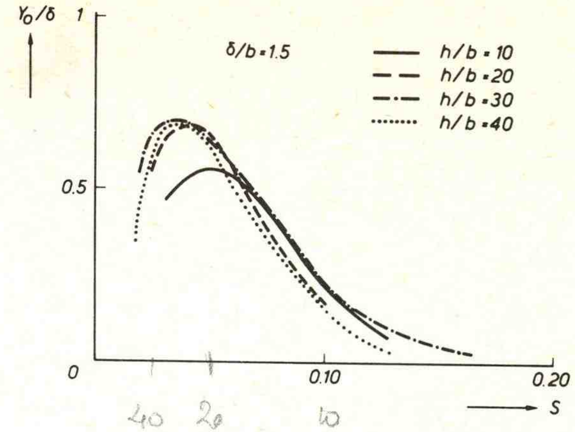

Fig. 5 Maximum equilibrium amplitudes
Maxima des amplitudes d'équilibre

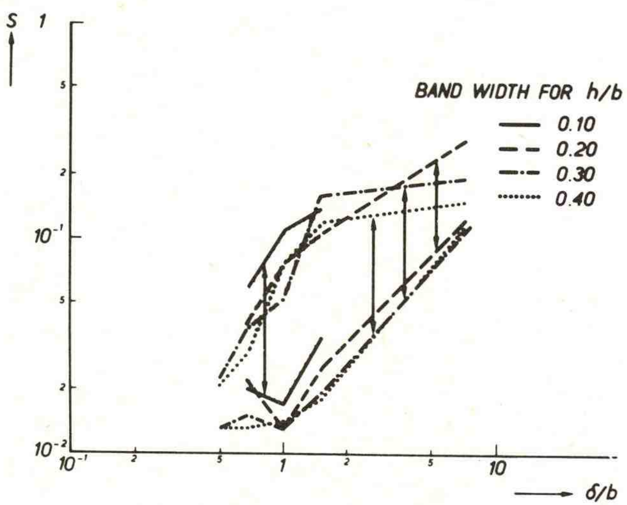

Fig. 6 Critical range of S for different gate raises
Zône critique de S pour les différantes ouvertures
de la vanne

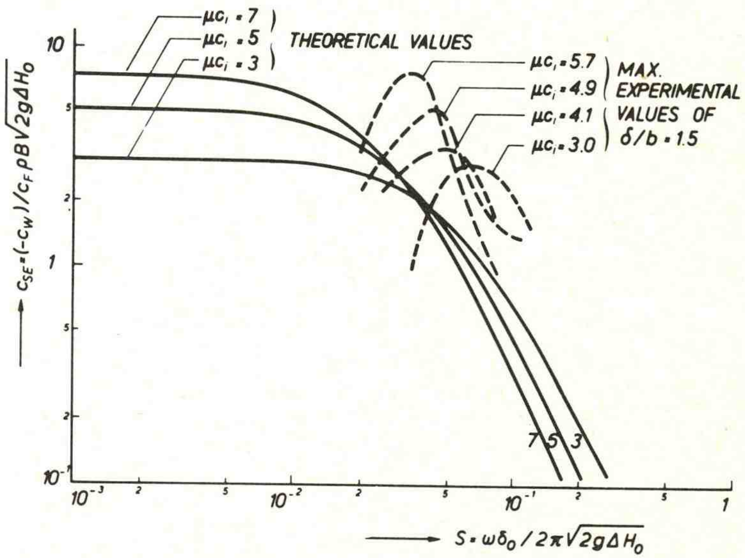

Fig. 7 Self-excitation coefficient
Coefficient de l'auto-excitation

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