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A BALANCING SEPARATOR FOR THE AMMONIA THERMOCHEMICAL ENERGY TRANSFER DEMONSTRATION

MASTER

Energy Conversion Technical Report No. 26

by

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INSTITUTE OF ADVANCED STUDIES

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CONTENTS

1. INTRODUCTION

A separator, in the sense used here, is a vessel for receiving mixtures of gas (nitrogen, hydrogen and ammonia vapour) and liquid (liquid ammonia with small amounts of dissolved nitrogen and hydrogen) in which the liquid settles out in the bottom with the gas phase above. Provision is made for the separate extraction of each phase. It is important that the velocity of gas in the separator be low and that the path length between inlet and gas outlet be long so that entrained liquid particles may settle out.

The balancing separator is a separator whose mass may be determined by virtue of it being attached to a balancing arm on a fulcrum.

The many uses of such a device are described in the June 1982 Progress Report of the Ammonia Thermochemical Energy Demonstration (ref 1). Briefly these uses are: to enable absolute calibration of liquid and gas flow meters, to enable the determination of the nitrogen-to-hydrogen molar ratio of the gas, to enable the absolute determination of rates of dissociation and synthesis; and to provide an essential control element for the demonstration of an energy transferring system.

The basic principle is simple: a vessel is suspended from one end of a balance arm and a counter weight from the other. Any difference in torques generated by the two weights produces a reaction torque in a tortion rod attached at the fulcrum. The associated displacement is registered by a proximity gauge. The displacement may be reduced to zero by moving a weight along the arm. This weight is activated by a motor and screw and its position is recorded by a revolution counter which thus gives an indication of mass changes in the vessel.

2. DESCRIPTION

The drawing, Figure 1, shows the assembled balancing separator and all its components (numbered). A description of the construction and function of the more important of these components now follows.

2.1 Fluid Containment

(1) is the separator vessel of welded stainless steel having two ports at the top and one at the bottom. These connect to small stainless steel tubes (6) formed into helices and thence to the external fluid system. From a mechanical point of view these helices act like 'soft' springs. The helices are arranged in a symmetrical pattern so that anomalous mechanical effects cancel. The purpose of their attachment to the vessel by rigid arms is to eliminate anomalous horizontal forces (which cannot cancel). The inlet port at the top is fitted internally with a tube which carries fluid halfway down the vessel (the end may or may not be submerged). The gas outlet port, on the other hand, opens directly into the top of the vessel so that there is considerable distance between the two. The liquid outlet port at the bottom also opens directly into the vessel.

2.2 Balancing, Damping

The balance arm is divided into two: the short arm (37), and the long arm (38). The main fulcrum comprises two knife edge assemblies (32) (the knife edges are made from razor blades) and mating grooves (33). These are positioned either side of the balance arms so that the centre of gravity of the arms and moving weight lie in the same plane as the fulcrums. Components (33) are so constructed that their grooves self align with the knife edge.

The vessel is carried on a third knife edge and mating groove, (9) and (10) respectively.

The long arm (38) is shaped like a channel in which travels the moving weight (28) on the lead screw (23) which passes through its middle. (23) has two bearings mounted in (25) at the motor end, (two to increase the critical frequency of rotation) and one bearing (24) at the other end. The motor (19) is directly coupled to the lead screw at one end and the revolution counter (35) at the other.

Damper arms (58) are mounted directly over the main fulcrum so as to minimise the effects of forces produced by the displacement of fluid in the damping pots (60).

Tortion rods (43) are mounted in line with the main fulcrums and serve to positively locate the balance arms with respect to the stationary frame.

2.3 Detection of Displacement

Stationary platform (40) carries Bentley proximity gauge (39) which may be placed anywhere along the length of the platform (the design position being at the end nearer the motor).

The vertical height of the Bentley gauge is adjustable and the gauge senses the underside of the long arm (38). Two stop screws (55) limit the travel of the arm to the operating range of the Bentley gauge.

2.4 Lifting, Assembly, Disassembly

Screw (50) is for raising the pick-up (51) when the balance is not in use or during assembly or disassembly. The pick-up first lifts the vessel off its knife edge and then, in conjunction with the lower stop screw (55), relieves the load on the main fulcrum (substantial separation of the main knife edge from its groove is to be avoided unless the tortion rods are first removed). The main fulcrum components may then be removed followed by the tortion rods. Finally, after swinging the top screw (55) out of the way, the arm assembly may be removed.

3. OPERATION

There are two modes of operation: dynamic and static.

For the dynamic mode, the moveable weight is actually fixed. Any imbalance thus causes tortion in the tortion rods and a displacement measureable by the Bentley gauge. It is not expected that the gauge output will be linear with respect to mass changes in the vessel nor give an absolute indication of the magnitude of these changes. On the other hand the dynamic response is expected to be good and the motor and screw will not be subjected to wear in a prolonged dynamic situation.

In the static mode, the Bentley output is used as an error signal in a control loop which activates the motor in order to reduce the error signal to zero. In this case the position of the moveable weight, as indicated by the revolution counter attached to the lead screw, gives an absolute measurement of changes in the mass of the contents of the vessel.

The dynamic mode will be appropriate when the balancing separator is used as a control element in the energy transfer demonstration. In this case, the task of the control system will be to make the rate of synthesis follow the rate of dissociation. The balancing separator will be the common source of feedstock and the products of dissociation and synthesis will be returned to it. Therefore, equal rates of synthesis and dissociation will be manifested by a constant liquid level in the balancing separator, ie. by a constant mass. Thus deviations in mass will indicate an error in the rate of synthesis and will be made to increase or decrease the gas flow to the synthesiser and so affect the rate of synthesis in the direction to restore equality of rates.

In this application the Bentley gauge is a null detector in the overall control system. Therefore, some non-linearity is tolerable as too is a degree of uncertainty in the calibration of the Bentley output.

The static mode will be used in all measurements eg. calibration of flow meters, measurement of molar ratio of gas. In every such instance the counter will be read when the moveable weight is stationary eg. before and after switching a steady fluid flow into the vessel as would be the case when calibrating a flow meter.

4. SPECIFICATION

In this section is presented the performance figures aimed for and the derivation of the figures where this is appropriate

4.1 Primary Characteristics, Values and Symbols

Symbol	Value	Characteristic	Referenced Section
a	50 mm	Short arm length	4.3.2
b	400 mm	Long arm length to Bentley	4.3.2
b_c	200-400 mm	Long arm length to counterweight	4.5.1
B	8000 v/rad	Displacement detection sensitivity	4.2.5
d	0.02 mm	Diameter of knife edge	4.5.1
D	0.91 Nms	Damping factor (critical)	4.4

f_r	2.12 Hz	Natural frequency	4.4
g	9.81 ms^2	Gravity acceleration	
G_r	0.21	Open circuit loop gain at resonant frequency	4.4
I	0.068 kg m^2	Moment of inertia	4.4
K	12.05 Nm/rad	System spring constant	4.3.1
l	38 mm	Length of knife edges	4.5.1
m	30 gm	Moving mass	4.3.2
M	≈ 3 kg	Vessel mass	4.2.1
M_g		Mass of gaseous contents of vessel	4.7
M_{g_o}	18.1 gm	Value of M_g for stochiometric mix of $N_2 + H_2$	4.7
M_s	≈ 3.7 kg	Total suspended mass	4.5.1
ΔM		Symbol for error in M	4.6
n		Number of moles in vessel	4.7
p	0.7 mm	Pitch of lead screw	4.2.4
P	15 MPa	Working pressure	4.2.1
Q	20 revs/sv	Speed sensitivity of motor and power amp	4.2.6
r_1		Radius of convex fulcrum surface (knife edge)	4.6.4

r_2		Radius of concave fulcrum surface	4.6.4
R		Gas constant	4.7
S	0.42 gm/rev	Screw sensitivity	4.2.4
T	293^0K	Absolute temperature	4.7
Δv	83 mv	Minimum starting voltage	4.6
V	358 cc	Vessel volume	4.2.1
x		Mole fraction of H_2	4.7
Δx	1.8%	Error in determination of x	4.7
α		Fractional increase of r_2 over r_1	4.6.4
μ	0.2	Coefficient of friction in fulcrums	4.5.1
σ_b	48 MPa	Nominal bearing stress in knife edges	4.5.1
σ_c	$\approx$200 MPa	Physical limit to local compressive stress	4.6.4
ϕ		Angle of rotation of balance arm	4.6.4
ψ		Angular position of contact point on knife edge	4.6.4
ω_r	13.31 rad/s	Natural frequency	4.4

4.2 Components

4.2.1 Vessel

Construction:	welded stainless steel
Design pressure:	24 MPa
Working pressure:	P = 15 MPa
Internal length:	300 mm
Internal volume:	V = 358 cc
Mass:	$M \approx 3$ kg
Calibration time for gas:	5.17 s

This is the time to pass 358 cc at a gas pressure of 15 MPa and flow rate 3.5 gm/s, the design maximum for the system.

4.2.2 Flexible connectors

Construction: 3.18 mm OD SS tubing 2.36 mm ID formed into helices

Helix diameter:	190 mm
Spring constant referred to fulcrum (for 3 helices):	0.32 Nm/rad
Pressure drop per connection for gas at 3.5 gm/s, 15 MPa:	80 KPa
Internal volume of each connection as fraction of vessel volume:	2.57%

4.2.3 Tortion rods

Material:	steel
Number:	2
Length of each:	76 mm
Diameter:	2.4 mm
Spring constant:	11.72 Nm/rad

4.2.4 Lead screw: The following are design values:

Thread:	4 mm metric
Pitch:	p = 0.7 mm

Backlash: $\pm$ 1/6 turn ie. $\pm$ 0.12 mm

Screw sensitivity: S = 0.42 gm/turn

This is calculated from

$$S = \frac{p.m}{a}$$

where m is the moving mass and p is the screw pitch.

For p = 0.7 mm and m = 30 gm

$$S = 0.42 \text{ gm/turn}$$

4.2.5 Displacement detection

Detector: Bentley proximity gauge

Position: 400 mm along long arm

Range: 0 to 0.5 mm, 0 to 10 volts

Sensitivity: B = 8000 v/rad

4.2.6 Motor and power amplifier characteristics

The following are design values. Voltages are input voltages to the motor power amplifier.

Speed sensitivity: Q = 20 revs/sv

In the control loop the motor amplifier is connected to the Bentley gauge output. Therefore, this characteristic can be regarded as meaning that 20 revs/sec corresponds to 1 volt from the Bentley gauge in the linear range of both.

Maximum speed: 2000 rev/min

The design limit here is dictated by considerations such as the critical rotational speed of the lead screw.

Maximum voltage: 1.67 v

This is relevant to the motor voltage limiting circuit needed to limit the speed.

Minimum starting voltage: 84 mv

Maximum torque required: 1 x 10 Nm

(due almost exclusively to the counter)

Specification of Chosen Motor Escap 22C11-216E.1

Speed sensitivity: 16.67 revs/sv

Implied gain of power amplifier: 1.2

Mechanical time constant: 21 ms

Maximum speed: 5900 revs/min

Maximum power: 1.6 W

Maximum voltage: 6 v

Starting voltage: 100 mv

Starting voltage referred to input of amplifier, gain 1.2: 83 mv

Stall torque: 10.2×10^{-3} Nm

4.3 System Characteristics

4.3.1 System spring constant:

Level of C of G of suspended system below level of main fulcrum: zero

System spring constant: K = 12.05 Nm/rad

(equal to sum of constants for tortion rods and flexible connections)

4.3.2 Static mode range

Difference in mass between vessel evacuated and vessel filled with liquid: 229 gm

Short arm length: a = 50 mm

Moving mass: m = 30 gm

Range of travel of moving mass: 400 mm

Range referred to mass of vessel contents: 240 gms

Long arm length to Bentley gauge: b = 400 mm

4.3.3 Dynamic mode range

Mass change: 30.7 gms

This is the mass change that will cause the Bentley output to move over its 10 v range. It is therefore calculated as 10 K/agB.

Liquid level change: 42 mm

Proposed coupling between synthesis gas flow and liquid level: 0.1 Kg/sm

(ie. 0.1 gm/s change in flow per mm level change). Thus a liquid level change of 42 mm corresponds to 4.2 gm/s gas flow. A separate study shows that this flow is sufficiently above the steady state maximum flow of 3.5 gm/s to cope with transients in a stable energy transfer system.

4.3.4 Effect of flexible connections on performance

Provided the density of the fluid contents of the flexible connections is constant along the length of the connection, half the contents of each connection will be attributed to the vessel contents by the mass measuring mechanism. This means that in this case the vessel boundaries are effectively located half way along each flexible connection. Uniform density would be expected to always occur in the outlet connections for liquid and gas respectively but may not always occur in the inlet connection where alternate slugs of liquid and gas are likely to pass. A slug of liquid may, for example, occupy exactly half the connection. If such a slug were positioned in the middle of the connection, again half its mass would be attributed to the vessel so there would be no error in assuming that the vessel boundary was at the halfway point. But if the slug were situated at the vessel end of the connection only about three quarters of its mass would be attributed to the vessel side of the boundary. The error in this case would be one quarter of the mass of the slug or one eighth of the mass of the contents of a filled connector. It can be shown that this is a 'worst case' example and that the maximum corresponding error is ± 0.7 gms.

Of course the occurrence of large discreet slugs of liquid and gas in the input stream will create a problem in measuring steady flows irrespective of whether there are flexible connections or not, in fact irrespective of the method of measuring flows, and may necessitate modifications elsewhere in the system.

4.4 Control Loop: Open Circuit Gain, Stability

Figure 2(a) is a diagram of the control loop. The balance function, shown dotted, relates the angular position of the balance arm ϕ to the net torque about the fulcrum T. This function contains the inertia constant I, the damping constant D and spring constant k and has a transfer function typical of a resonant system, in this case a critically damped resonant system. The resonant frequency is given by:

$$\omega_r = (k/I)^{\frac{1}{2}} \text{ rad/s}$$

or

$$f_r = \frac{\omega_r}{2\pi} \quad \text{Hz}$$

At well below resonance and well above resonance the approximations shown in Figure 2(b) for the balance function apply. When these are combined with the rest of the system, which has a single integration with time, one may construct the gain vs frequency and phase vs frequency graphs shown in Figure 3. The criterion for stable operation is that the gain at 180° phase shift must be less than unity which may be translated in our case to mean that the gain at resonance, G_r, must be less than unity.

We may calculate G_{res} by assuming that the linear regions of Figure 3 intersect at f_r. Thus

$$G_r = \frac{BQpmg}{\omega_r K} = \frac{BQpmg}{\omega_r^3 I}$$

Also since at resonance the gain would go to infinity if it were not for the presence of the damping factor, we require D to be such that

$$G_r = \frac{BQpmg}{\omega_r^2 D}$$

where $D = K/\omega_r = 0.91$.

For the values specified we find

$$G_r = 0.21$$

which is substantially less than unity.

4.5 Fulcrums

4.5.1 Main fulcrums

Materials: knife edge from steel razor blade
groove from hardened steel

The following are design figures:

Length of knife edges: $l = 38$ mm

Diameter of knife edge and matching groove: $d = 0.02$ mm

Suspended mass: $M_s = 3.7$ kg

Nominal bearing stress: $\sigma_b = 48$ MPa

(from $\sigma_b = \frac{M_s g}{ld}$

Coefficient of friction: $\mu = 0.2$

Shift in contact point due to friction circle: $\pm .002$

(from: friction circle radius $= \frac{d}{2} \sin \tan^{-1} \mu$)

Sensitivity to shift in contact point

$$\frac{dM}{da} = -\frac{M(a + b)}{ab}$$

where M = mass of vessel

a = short arm distance

b_c = long arm distance (to counter weight)

For M = 3 kg

a = 50 mm

b_C = 400 to 200 mm

$\frac{dM}{da}$ = - 67.5 to -75 gm/mm

Assume -70 gm/mm

Error due to friction: ± 0.14 gm

(See Section 4.6.4 for a more complete treatment of this error.)

4.5.2 Vessel fulcrum

The design specification for the vessel fulcrum is essentially the same as for the main fulcrum.

Sensitivity to shift in contact point:

For the vessel

$$\frac{dM}{da} = -\frac{M}{a} = -60 \text{ gm/mm}$$

Error due to friction: ± 0.12

4.6 Errors in Mass Determination

4.6.1 Slugging

Slugging error: ± 0.7 gms

This error arises from the fact that the balance includes in its determination of mass a fraction of the mass of the contents of the flexible connections. This fraction is unpredictable when slugs of liquid and gas reside in the connections and give rise to an error. The derivation is fully described in Section 4.3.7.

4.6.2 Starting voltage

Starting voltage error: ± 0.25 gm

In the static mode a minimum mass change ΔM of the vessel contents will be required to excite the motor to take corrective action.

If Δv is the minimum starting voltage, B the Bentley gauge sensitivity, K the system spring constant, and a the short arm length, we have

$$\Delta M = \frac{\Delta v K}{a B g}$$

For Δv = 83 mv

K = 12.05 Nm/rad

a = 50 mm

B = 8000 v/rad

g = 9.81 m/s^2

then ΔM = ± 0.25 gm

4.6.3 Backlash

Backlash error: ± 0.07 gm

This is calculated as the product of S and the backlash of ± 1/6 turn.

4.6.4 Fulcrum

Fulcrum error: ± 0.35 gm

If one considers a fulcrum as being a cylinder of radius r_1 located in a cylindrical groove of radius r_2, the motion of the contact point may be expressed as a function of the rotational motion of the balance arm. If there is no sliding at the contact, the angular position of the contact point relative to the convex surface, angle ψ, is related to the position of the beam ϕ by

$$\frac{d\phi}{d\psi} = \alpha \quad , \qquad \alpha \ll 1$$

where $$\frac{r_1}{r_2} = 1 + \alpha$$

It will be shown later that the size limit to α is justified in practice. Thus in this case the range of ϕ is small in comparison to the range of ψ and since ψ, when measured from the vertical, cannot exceed the friction angle $\tan^{-1}\mu$ without sliding, the corresponding non-sliding motion of the beam will be limited to $\alpha\tan^{-1}\mu$.

Although this limit is very small the motion of the beam may in fact be well within it because of the small range of the Bentley gauge for which $|\phi|$ need not exceed 0.62 mrads. Thus, assuming $\mu = 0.2$, sliding must occur only in the range $\alpha < 0.003$. Outside the range the mating fulcrum surfaces will probably be in rolling contact in which case the lateral shift in position of the contact point and the consequent error in mass determination will be less than the figures given in this specification. However, other factors must also be considered.

As α increases the local compressive stress σ_c will increase. An approximate formula for this has been derived from Roarke (ref 2) viz

$$\sigma_c/\sigma_b \approx 61\alpha^{\frac{1}{2}}$$

Thus, assuming $\sigma_c \leq 200$ MPa, we derive an upper limit to α of 0.0047. We conclude therefore that rolling occurs for $.0047 > \alpha > .003$ and it follows that under the best conditions of rolling contacts lateral motion of the contact will be about 0.64 times the figure for sliding. This conclusion will of course differ if d is changed from the specified value.

However, even if rolling occurs always during operation of the balance, there is no guarantee that $\psi = 0$ when $\phi = 0$. In fact, the outer limit of ψ could be at a point of incipient sliding with subsequent cyclical excursions due to rolling taking the contact towards $\psi = 0$ and back again.

Thus the friction limited figures given in the specification are valid long-term limits to accuracy.

It can be readily shown that the errors due to friction from both fulcrums are always cumulative.

We conclude therefore as follows:

Error due to fulcrums: $\pm$ 0.30 gm

4.6.5 Summary, mean error

The errors are the maximum differences in grams between the measured vessel mass and actual vessel mass due to the various causes.

Slugging in connectors:	$\pm$ 0.7 gm
Starting voltage of motor:	$\pm$ 0.25
Lead screw back-lash:	$\pm$ 0.07
Fulcrums:	$\pm$ 0.30

In considering the statistical summation of these errors it is unlikely that the total error will exceed $\pm$ 1 gm. In many applications eg. flow calibration and the determination of the N-to-H molar ratio, the slugging error is not applicable in which case the statistical summation of the remaining errors may be taken as 0.5 gm.

4.7 Precision for Determination of N-to-H Molar Ratio: ± 1%

The derivation of this figure is as follows.

Suppose a mixture of gas is known to contain only nitrogen and hydrogen. Let x = mole fraction of hydrogen, then (1 - x) = mole fraction of nitrogen. The total number of moles n is

$$n = PV/RT$$

where V is the volume of the vessel. Therefore the total mass of gas M_g is:

$$M_g = (28 - 26x)PV/RT$$

and

$$\frac{dM_g}{dx} = -26PV/RT = -3.06\ M_{g_o}$$

where M_{g_o} is the value of M_g for the stoichiometric mixture (x = .75). For the vessel in question M_{g_o} = 18.1 gms. Therefore the error in mole fraction Δx is related to the error in mass measurement Δm by

$$|\Delta x| = 0.018\ \Delta M$$

and for $\Delta m = \pm 0.5$ gm we have

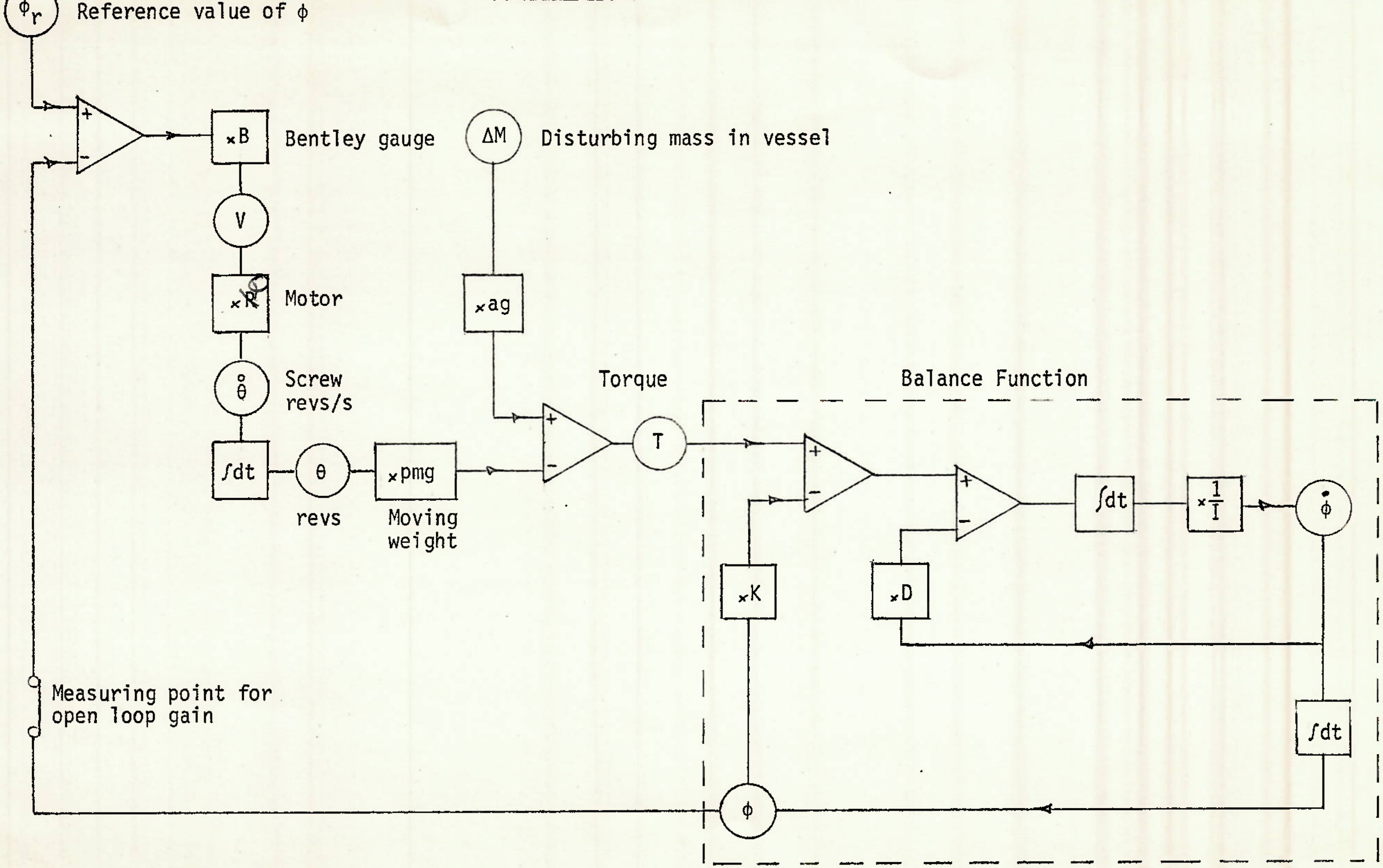
$x = \pm 0.9\%$.

REFERENCES

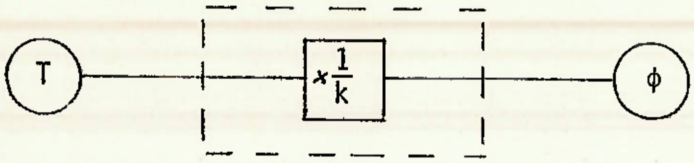
1. P O Carden, 'Thermochemical energy transfer (chemical heat pipe) demonstration based on the system $2NH_2$ $N_2 + 3H_2$', Progress Report, Department of Engineering Physics, ANU, June 1982.

2. R J Roark, 'Formulas for stress and strain', 3rd ed, McGraw Hill, 1954, Case 6, p 288.

FIGURE 2(a): Diagram of control loop



Balance Function at Low Frequency



Balance Function at High Frequency

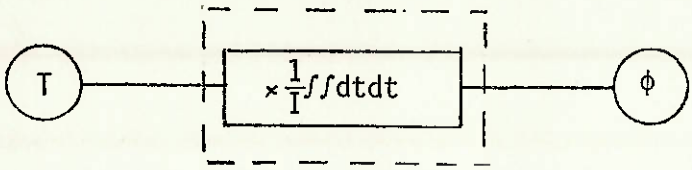


FIGURE 2(b)

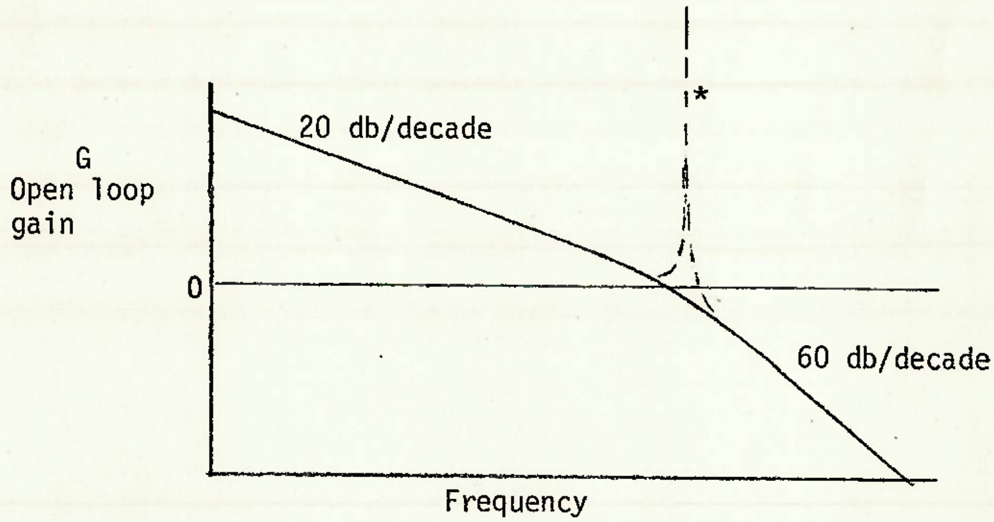
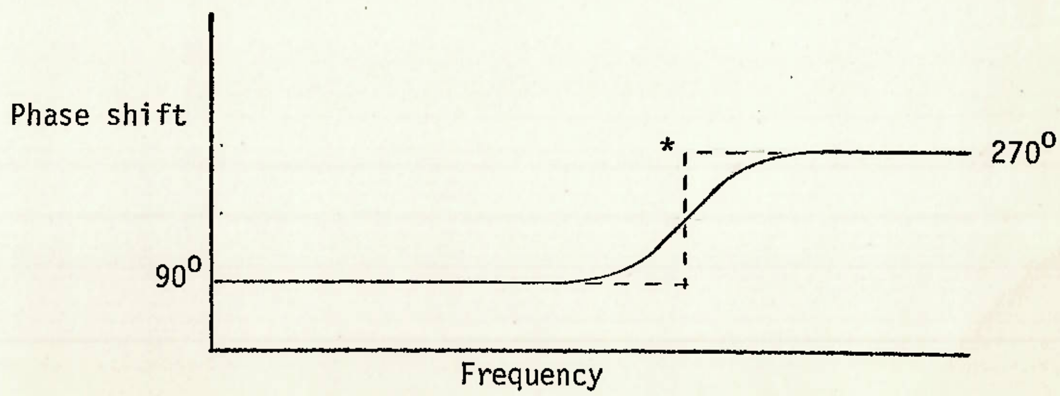


FIGURE 3: Gain and phase vs frequency



* Dashed lines indicate position of resonance (if damping were negligible)