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DYNAMIC CALIBRATION OF TURBINE FLOWMETERS BY MEANS OF FREQUENCY RESPONSE TESTS

by Grady H. Stevens

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Cleveland, Ohio

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ABSTRACT

A technique for dynamic calibration of turbine flowmeters for small-amplitude sinusoidal perturbations was investigated. The investigation included a theoretical analysis and an experimental evaluation of a typical flowmeter for a range of frequencies and mean flow rates. The indicated flow was related to the actual flow by a first-order lag function. This lag function was completely defined by a breakpoint frequency which was directly proportional to mean flow rate. The proportional constant was determined experimentally for a typical flowmeter. This calibration constant was sufficient for completely specifying the flowmeter dynamics over the range of mean flows investigated.

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SUMMARY

A technique for dynamic calibration of turbine flowmeters for small amplitude sinusoidal perturbations was investigated. The investigation included a theoretical and experimental evaluation of a typical flowmeter for a range of frequencies and mean flow rates. The indicated flow was related to the actual flow by a first-order lag function. This lag function was completely defined by a breakpoint frequency which was directly proportional to mean flow rate. The proportional constant was determined experimentally for a typical flowmeter. This calibration constant was sufficient for completely specifying the flowmeter dynamics over the range of mean flows investigated.

INTRODUCTION

Turbine flowmeters are occasionally used to measure dynamic flow rates of liquids. The accuracy of such dynamic measurements is questionable without a dynamic calibration of the flowmeter and indicating apparatus.

Techniques for evaluating this performance have been proposed (refs. 1 and 2). These techniques determine the flowmeter response to large step changes in flow rate. Unfortunately, step changes in flow rate having short rise times are difficult to realize (ref. 1). It is possible to simulate a step change by suddenly releasing the turbine from rest in a flowing stream (ref. 2). However, repeatable data are difficult to obtain, especially at low flow rates.

The subject of this report is an alternate technique for obtaining a flowmeter calibration. A 3/8-inch (0.952-cm) flowmeter, similar to that described in reference 3, was calibrated at the NASA Lewis Research Center. The calibration was obtained by sinusoidally perturbing the liquid flow rate through a line terminated with an orifice.

The flow indicated by the flowmeter was compared with that obtained from the orifice-pressure-drop measurements. This technique has the advantages that it employs easily obtained sinusoidal perturbations, and it provides repeatable results.

SYMBOLS

A cross-sectional area of calibration line, in.^{2}; m^2

A_t cross-sectional area of flowmeter in vicinity of flowmeter turbine, ft^2; m^2

e_w average value of converter output which was proportional to frequency of converter input signal, V

f perturbation frequency, Hz

f_o breakpoint frequency of flowmeter, Hz

G_c frequency converter and band-pass filter conversion constant, $\tilde{e}_w/\tilde{\Omega}$, V/rad

G_F flowmeter calibration constant, $\tilde{\Omega}/\tilde{W}$, rad/lbm; rad/kg

h_1 length of calibration line, in.; m

K_1 constant dependent on flowmeter geometry, ft/lbm; m/kg

K_2 constant dependent on flowmeter geometry, dimensionless

K_3 constant dependent on flowmeter geometry, ft; m

L inertance of calibration line, (psi-sec^2)/(lbm-rad); (N-sec^2/m^2)/(kg-rad)

P_1 upstream pressure of calibration line, psig; N/m^2 gage

P_2 pressure at exit of calibration line orifice, psig; N/m^2 gage

R dynamic resistance parameter of calibration line, $2(\overline{P_1 - P_2})/\overline{W}$, psi/(lbm/sec); (N/m^2)/(kg/sec)

U velocity of fluid in vicinity of flowmeter turbine, ft/sec; m/sec

W actual mass flow, lbm/sec; kg/sec

W_i indicated mass flow rate, lbm/sec; kg/sec

Ω angular velocity of turbine flowmeter, rad/sec

ω perturbation frequency, rad/sec

ρ fluid density, lbm/ft^3; kg/m^3

θ angular position of flowmeter turbine, rad

Superscripts:

— mean value

perturbations about mean

THEORETICAL RESPONSE OF FLOWMETER

An analysis by Grey (ref. 3) showed that the angular position θ of the flowmeter turbine is related to liquid velocity U by an equation of the form,

$$K_1 \rho U^2 \left[K_2 - \left(\frac{K_3}{U} \right) \frac{d\theta}{dt} \right] = \frac{d^2\theta}{dt^2} \tag{1}$$

The effects of fluid viscosity and bearing friction are disregarded in equation (1).

The turbine angular velocity Ω is given by

$$\Omega = \frac{d\theta}{dt}$$

and the liquid mass flow rate W is given by

$$W = \rho A_t U$$

Making these substitutions into equation (1) results in

$$\left(\frac{K_1 K_2}{\rho A_t^2} \right) W^2 - \left(\frac{K_1 K_3}{A_t} \right) W\Omega = \frac{d\Omega}{dt} \tag{2}$$

Equation (2) is, in general, nonlinear. However, it reduces to a linear equation for two cases. Grey solved this equation (in slightly different form) for the case of a step change in flow rate (W can be treated as if it were constant for that case, and eq. (2) is linear). Generally, W varies continuously, and this simplification is not possible. However, if small perturbations in W and Ω are assumed, equation (2) can be linearized by substituting

$$\Omega = \overline{\Omega} + \Omega'$$

$$W = \overline{W} + W'$$

and disregarding the products of perturbations. The resulting linear equation is

$$\Omega' + \left(\frac{A_t}{K_1 K_3 \overline{W}}\right) \frac{d\Omega'}{dt} = G_F W' \tag{3}$$

where

$$G_F = \frac{K_2}{K_3 A_t \rho}$$

The analytical frequency response of the flowmeter can be obtained directly by substituting ($j\omega$) for the differential operator (d/dt).

Therefore the analytical frequency response is given by

$$\Omega' = \left(\frac{1}{1 + j\,\frac{f}{f_o}}\right) G_F W' \tag{4}$$

where f is the perturbation frequency and

$$f_o = \left(\frac{K_1 K_3}{2\pi A_t}\right) \overline{W} \tag{5}$$

is the breakpoint frequency of the flow to angular velocity transfer function (eq. (4)). Equation (5) shows that the breakpoint frequency is directly proportional to the mean flow rate.

The angular velocity in equation (4) was converted to an electrical signal by means of a magnetic pickup. The electrical output was a sine wave with a frequency and amplitude proportional to the turbine angular velocity.

This sine wave output can be processed by a frequency-to-voltage converter and a band-pass filter (see EXPERIMENTAL APPARATUS section). When thus processed, the band-pass filter isolated the sinusoidal voltage proportional to the sinusoidal perturbation in turbine angular velocity. This flow signal is of the form

$$e'_W = \left(\frac{1}{1 + j \frac{f}{f_o}} \right) G_c G_F \frac{W'}{2}$$

where

$$G_c = \frac{\bar{e}_W}{\bar{\Omega}}$$

and the factor 1/2 is introduced by the band-pass filter. Taking the ratio of e'_W and $(G_c G_F)/2$, the result is

$$W'_i = 2 \frac{e'_W}{G_c G_F} = \frac{W'}{1 + j \frac{f}{f_o}} \tag{6}$$

where W'_i is the perturbation mass flow indicated by the flowmeter.

Equation (6) shows that the indicated flow is a first-order lag function of the actual flow where the breakpoint frequency f_o is proportional to the mean flow rate (eq. (5)). This equation implies that the breakpoint frequency f_o for a particular flow rate, can be obtained by fitting a first-order lag function to the experimental ratio of W'_i to W' as a function of frequency. In addition, equation (5) implies that a plot of the resulting breakpoint frequencies as a function of mean flow will yield an experimental value for the calibration constant, which is given analytically by

$$C = \frac{K_1 K_3}{2\pi A_t}$$

This constant is dependent only on flowmeter geometry.

EXPERIMENTAL APPARATUS

General

The apparatus used to obtain the flowmeter calibration is shown in figure 1. The mean flow was established by the gear pump downstream of the storage tank. The flow disturbances generated by the gear pump were attenuated by the accumulator upstream of the throttle valve. The accumulator also acted as a quasi-constant pressure source for the calibration line and throttle valve. The flow rate was sinusoidally perturbed by perturbing the open area of the throttle valve. An indication of the flow perturbation was obtained with the flowmeter and also from the orifice pressure drop.

A reservoir was placed at the exit of the line. This reservoir maintained a constant-head exit condition for the orifice by means of a spillway and a vent to the atmosphere. A plastic window was attached to the side of the reservoir so that the condition of the liquid flow exhausting through the orifice could be determined.

Dynamic Instrumentation

A block diagram of the dynamic instrumentation is shown in figure 2. As shown in the figure, the pressure and flowmeter signals were processed by a frequency-response analyzer. The analyzer computed the magnitude and phase of each signal with respect to a reference sinusoid generated within the analyzer. The reference frequency also actuated the throttle-valve control apparatus.

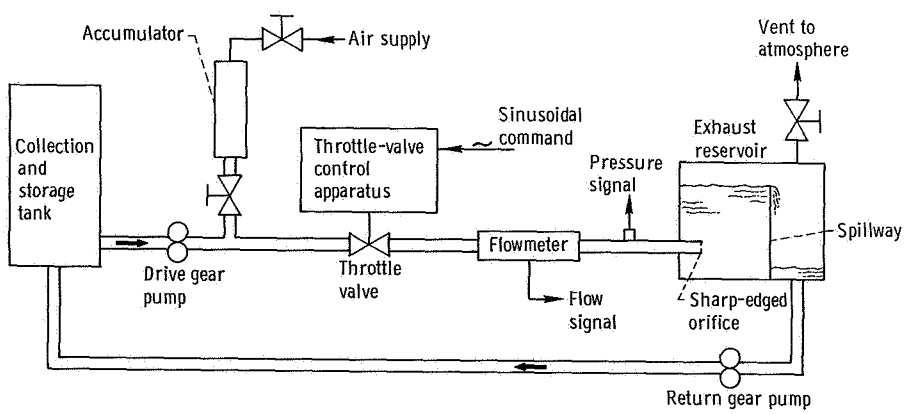


Figure 1. - Dynamic calibration test rig.

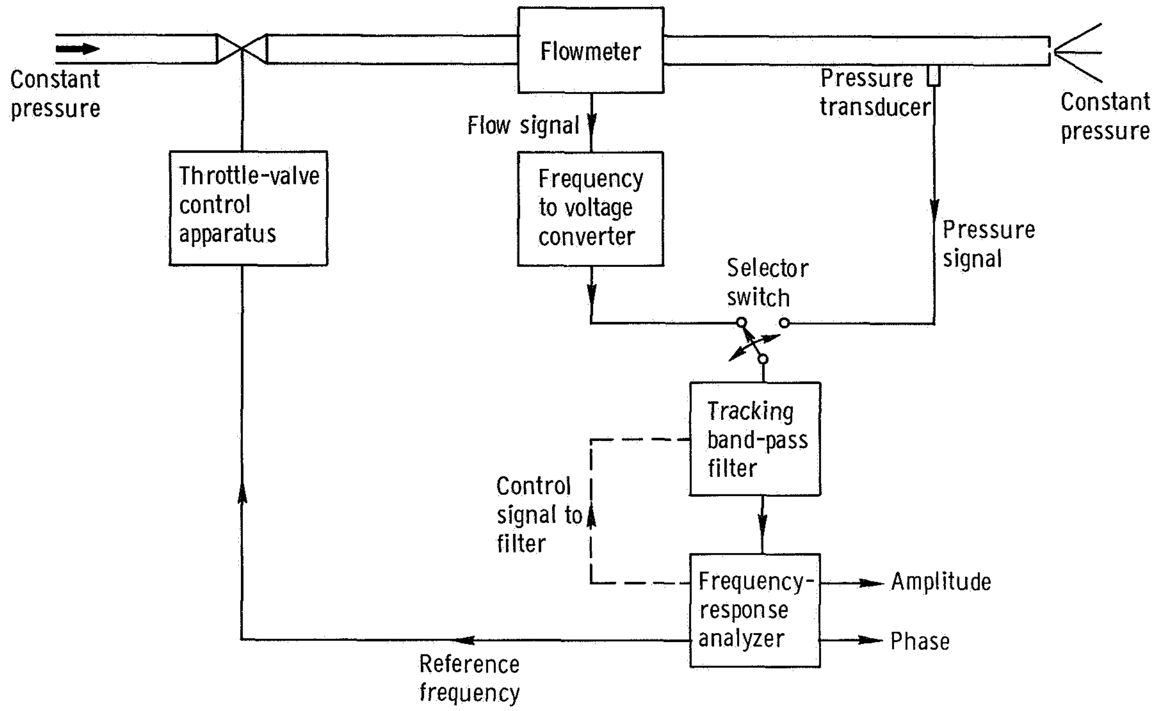


Figure 2. - Block diagram of dynamic instrumentation.

Both signals were processed by a band-pass filter. The filter was electrically coupled to the frequency-response analyzer so that the pass band was always centered about the reference frequency. Thus, the desired sinusoidal signals were passed without phase error.

The frequency to voltage converter, used to process the flowmeter signal, was a type that also minimized phase error. The converter produced a constant amplitude, constant width pulse for each cycle of the input signal. The converter output was filtered by the band-pass filter. (This contrasts with the usual case where a low pass filter is an integral part of the converter. Such filters cause a serious loss in response.) The band-pass filter isolated the sinusoidal component of the converter output which was proportional to the sinusoidal perturbation of turbine angular velocity. All other components were attenuated.

PROCEDURE

A series of frequency response tests were performed for each of a series of mean flow rates. The mean flow rate for each frequency-response test was established by the drive gear pump (fig. 1). After the mean flow was set, the accumulator was pressurized and opened to the calibration line. The throttle valve was activated and operated over a range of frequencies, typically 0.1 to 10.0 hertz. For each frequency, the flowmeter and pressure signals were analyzed by a frequency-response analyzer. The analyzer computed the phase and amplitude of each signal with respect to the internal reference sinusoid.

The indicated flow W_i' was determined from the electrical output of the flowmetering system (flowmeter - converter - band-pass filter), e_W', and the calibration constants of the system from equation (6),

$$W_i' = \frac{2e_W'}{G_c G_F}$$

The actual flow W' was determined from the orifice pressure drop. W' was corrected for the effects of the inertia of the liquid between the orifice and pressure transducer (appendix).

The amplitude ratio of indicated flow W_i' to actual flow W' and phase difference as a function of frequency and mean flow rate were used to obtain the flowmeter calibration.

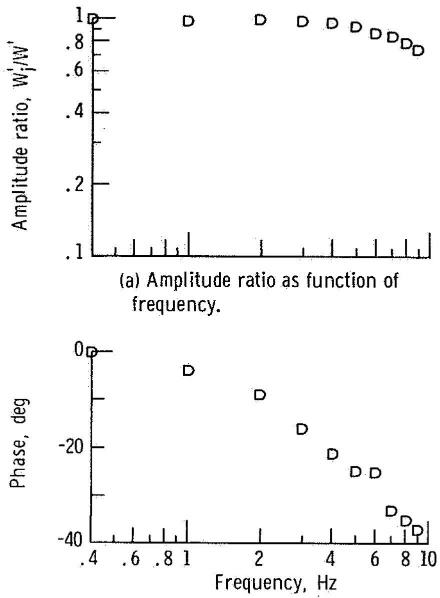
RESULTS AND DISCUSSION

A typical flowmeter frequency response is shown in figure 3. This set of data was obtained for a mean flow of 0.0605 pound mass per second (0.0275 kg/sec).

The amplitude ratio generally falls off as frequency increases as shown in figure 3(a). Also, the flowmeter introduces a phase error that becomes larger as frequency increases (fig. 3(b)). These curves are characteristic of a first-order lag function. The rate at which the amplitude ratio decreases and the rate at which the phase error increases, is determined by the breakpoint frequency f_o. Establishing the value of f_o completely defines the system dynamics for a particular flow rate.

A value for f_o obtained from the best fit of the data to a first-order lag function was evaluated for a range of mean flow rates. The result is shown in figure 4. The data of figure 4 were taken for two different orifice sizes. The duplication of test conditions provided a check on the repeatability of the data. Figure 4 shows that the breakpoint frequency is proportional to mean flow rate. This agrees with the analytical model (eq. (5)) where

$$f_o = \left(\frac{K_1 K_3}{2\pi A_t}\right) \overline{W}$$



(a) Amplitude ratio as function of frequency.

(b) Phase as function of frequency.

Figure 3. - Typical frequency response of turbine flowmeter.

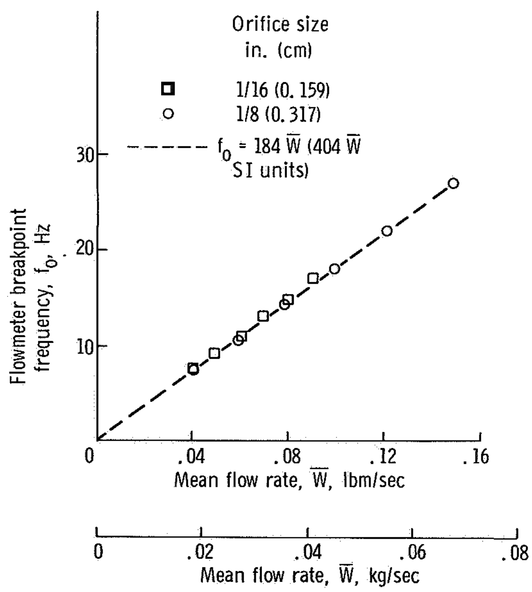


Figure 4. - Flowmeter breakpoint frequency as function of mean flow rate.

The quantity $(K_1K_3/2\pi A_t)$ for the data shown in figure 4 is 184 hertz per pound mass per second (404 Hz/(kg/sec)). This constant completely specifies the dynamics of the flowmeter for small perturbations. For the particular flowmeter tested, the actual flow W' can be determined from the indicated flow W_i' by reversing equation (6) and inserting the empirical value for f_o. The result is

$$W' = \left(1 + j\frac{f}{184\,\overline{W}}\right) W_i'$$

for U.S. Customary units and (7)

$$W' = \left(1 + j\frac{f}{404\,\overline{W}}\right) W_i'$$

for SI units.

Thus, a dynamic calibration of turbine flowmeters for small perturbations can be expressed by a single constant determined by means of frequency-response tests.

CONCLUSIONS

Turbine flowmeters can be calibrated dynamically by means of frequency-response tests, provided small perturbations are used. The calibration can be obtained in terms of a single constant. The flowmeter response is a first-order lag function. The break-point frequency is equal to the product of the calibration constant and the mean flow rate.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 31, 1968,
120-27-04-22-22.

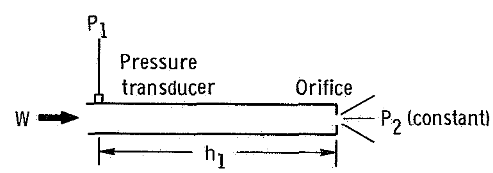
APPENDIX - DETERMINATION OF FLOW PERTURBATION FROM ORIFICE PRESSURE DROP

The actual flow perturbation W' was calculated from the orifice-pressure-drop perturbation. The calculation was based on the electrical analogy which is shown in figure 5. The inductance is equivalent to the inertia of the liquid between the orifice and pressure transducer. The resistance is related to the orifice pressure drop. Assuming a square-law pressure-drop curve (This was checked experimentally and found to be true for the range of flow rates tested.), the resistance was given by

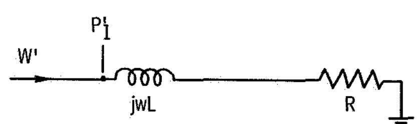
$$R = \frac{2\overline{(P_1 - P_2)}}{\overline{W}}$$

The inductance was given by

$$L = \frac{7.2\times10^{-7}\, h_1}{A}$$



(a) Calibration line.



$R = 2\overline{(P_1 - P_2)}/\overline{W}$

$L = 7.2\times10^{-7}\, h_1/A$

(39.3 h_1/A, SI units

(b) Electrical equivalent of calibration line for small perturbations.

Figure 5. - Calibration line and electrical equivalent.

and for SI units

$$L = \frac{39.3\ h_1}{A}$$

Using the analogy, the actual flow was calculated from

$$W' = \left(\frac{1}{1 + j\ \frac{\omega L}{R}}\right)\frac{P'_1}{R}$$

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