NASA TECHNICAL NOTE

NASA TN D-5565

c. 1

NASA TN D-5565

EFFECT OF STEADY VELOCITIES ON THE DYNAMIC RESPONSE OF LIQUID JET ATOMIZATION

by Marcus F. Heidmann

Lewis Research Center

Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1969

1. Report No. NASA TN D-5565	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECT OF STEADY VELOCITIES ON THE DYNAMIC RESPONSE OF LIQUID JET ATOMIZATION		5. Report Date December 1969
		6. Performing Organization Code
7. Author(s) Marcus F. Heidmann		8. Performing Organization Report No. E-5315
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 128-31
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The effect of steady axial, tangential, and radial velocities on the dynamic response of liquid jet atomization rate to pressure oscillations in a traveling transverse acoustic mode is analyzed. High axial velocity differences between the liquid and gas degrade the response. Tangential velocities in the direction of wave travel and radial velocities either toward the center or wall significantly increase peak response properties, whereas counterwave tangential flows suppress the response. The results imply that injection velocities and any lateral velocities caused by nonuniform propellant distribution, acoustic streaming, or acoustic damping devices can affect the stability of rocket combustors.

17. Key Words (Suggested by Author(s)) Liquid jet dynamics Combustion response Combustion instability		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22. Price* $3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

EFFECT OF STEADY VELOCITIES ON THE DYNAMIC RESPONSE OF LIQUID JET ATOMIZATION *

by Marcus F. Heidmann

Lewis Research Center

SUMMARY

The effect of steady axial, tangential, and radial velocities on the dynamics of liquid jet atomization in a traveling transverse acoustic mode is analyzed to examine the influence of steady velocities on the stability of rocket engine combustors. The analysis assumes an atomization model prescribing jet breakup when jet distortion caused by aerodynamic forces attains a critical value.

An increase in the axial velocity difference between the gas and liquid jet degrades the response of atomization rate to pressure oscillations. The effect of lateral velocities on response is more pronounced. Small tangential velocities in the direction of the acoustic wave travel and small radial velocities either toward the wall or toward the center significantly increase the magnitude of the response. Tangential velocities counter to the wave travel cause a substantial reduction in response.

The results imply that variations in injection velocities or axial gas velocities can alter stability properties of rocket combustors. Stability properties should also be sensitive to small lateral velocities near the injector caused by nonuniform propellant injection or acoustic damping devices and by the acoustic streaming velocities associated with acoustic modes.

INTRODUCTION

In previous analyses (refs. 1 and 2), the dynamic response of liquid jet atomization to acoustic oscillations associated with traveling, standing and radial transverse acoustic modes was presented. An atomization model (ref. 3) prescribing jet breakup when jet distortion caused by aerodynamic forces attains a critical value was used. The per-

*Presented at Sixth ICRPG Combustion Conference, Sept. 9-11, 1969, Illinois Institute of Technology, Chicago, Ill.

turbating or acoustic particle velocities were found to affect significantly the in-phase response factor (mass release in-phase with the pressure perturbation) of the process. Particle velocities in-phase with the pressure perturbation increased the response factor above the pressure sensitive value, whereas out-of-phase velocities were suppressive. The analytical solutions obtained for these nonlinear (pressure amplitude dependent) velocity effects have provided some insight into the parameters which can contribute to the stability of rocket combustors.

The analytical procedures used to extract particle velocity effects are also adaptable to examine steady velocities superimposed on the acoustic terms. Some steady velocity effects were previously reported. In the present study, a more general analysis of steady velocity effects on liquid jet response is presented. Axial, tangential, and radial velocities are treated. Principle extension of the previous analysis is with regard to steady radial velocities.

Steady velocities are often suspected and sometimes known to affect the stability characteristics of rocket engine combustors. Instability has been initiated in research combustors by inducing a steady tangential velocity as in references 4 and 5. Tangential and radial gas injection from the wall has also been used to trigger instability in full-scale combustors (ref. 6). Such gas injection is usually most effective in the region near the injector, where propellants are atomized. In addition to these induced velocities, steady flow effects on stability are often indirectly implied. Changes in stability behavior with injection velocity and contraction ratio may be examined from the viewpoint of changes in steady axial velocities. In some instances, recirculation near the injector is suspected to affect stability (ref. 7). Propellant distribution patterns are believed to be responsible for recirculation and a variety of steady transverse velocities. Baffles, acoustic liners, and circumferential slots may also alter steady flow patterns and thereby influence stability characteristics.

Because of the variety of steady flow conditions which can exist in a rocket combustor, this analysis attempts to provide some insight into how such steady flows can affect the dynamic response of the atomization process. The analysis has been directed toward steady velocities in traveling transverse acoustic modes. General analytical solutions are derived and specific evaluations are presented for some representative operating conditions.

ANALYSIS

The atomization model used is identical to that for the previous analyses of jet atomization (refs. 1 and 2). Aerodynamic pressure acting on an element of jet length causes an internal acceleration of liquid which eventually leads to breakup (see fig. 1)

If breakup is assumed to occur when displacement or distortion attains a critical value, the criterion for breakup of a continuous flow of jet elements is

$$\frac{\delta}{D} = \frac{2}{\rho_l D^2} \int_{t-\tau}^{t} \int_{t-\tau}^{t^*} f(t) dt^{**} \, dt^* = \text{Constant} \tag{1}$$

and the perturbation in atomization rate w, caused by fluctuations in aerodynamic loading as derived in reference 1, is

$$w' = -\frac{d\tau}{dt} = \frac{\int_{t-\tau}^{t} f(t) dt}{\tau f(t - \tau)} - 1 \tag{2}$$

where

$$f(t) = \rho_g V^2 = \rho_g \left(\left| u_l - u_z \right|^2 + u_r^2 + u_\theta^2 \right) \tag{3}$$

(All symbols are defined in the appendix.) The parameter V is the magnitude of the relative velocity vector between the gas and the liquid.

For this analysis, steady radial and tangential velocities are assumed to be superimposed on the first order acoustic expressions for the traveling transverse mode. The modified acoustic properties are

$$\left.\begin{aligned} \rho_g &= \bar{\rho}_g \left[1 + \hat{\rho}_g' \cos(\omega t + \theta) \right] \\ P &= \bar{P} \left[1 + \hat{P}' \cos(\omega t + \theta) \right] \\ u_r &= \bar{u}_r - \hat{u}_r \sin(\omega t + \theta) \\ u_\theta &= \bar{u}_\theta + \hat{u}_\theta \cos(\omega t + \theta) \end{aligned}\right\} \tag{4}$$

where

$$\hat{P}' = 1.72 \, J_1(\alpha) \hat{P}_w'$$

$$\hat{\rho}'_g = \frac{1}{\gamma} \hat{P}'$$

$$\hat{u}_r = 1.72 \frac{c}{\gamma}\left[J_0(\alpha) - \frac{J_1(\alpha)}{\alpha}\right]\hat{P}'_w$$

$$\hat{u}_\theta = 1.72 \frac{c}{\gamma} \frac{J_1(\alpha)}{\alpha} \hat{P}'_w$$

In the notation used, $\bar{u}_r$ is a positive steady radial velocity toward the wall, and $\bar{u}_\theta$ is a positive tangential velocity in the direction of the acoustic wave rotation.

The expression for the $\rho_g V^2$ force defined by the acoustic properties of equation (4) can be reduced to a harmonic series. Disregarding second and higher harmonic terms, the expression is

$$\rho_g V^2 = \bar{\rho}_g V^2_{rms} \left\{1 + 1.72 \frac{1}{\gamma} J_1(\alpha)\hat{P}'_w\left[\hat{V}_1 \cos(\omega t + \theta) - \hat{V}_2 \sin(\omega t + \theta)\right]\right\} \tag{5}$$

where

$$V^2_{rms} = \left|u_l - u_z\right|^2 + \bar{u}^2_r + \bar{u}^2_\theta + \frac{1}{2} \hat{u}^2_r + \frac{1}{2} \hat{u}^2_\theta + \left(\frac{1}{\gamma} 1.72\, J_1(\alpha)\hat{P}'_w\right)^2 \frac{c\bar{u}_\theta}{\alpha} \tag{6}$$

$$\hat{V}_1 = \frac{1}{V^2_{rms}}\left(\left|u_l - u_z\right|^2 + \bar{u}^2_r + \bar{u}^2_\theta + \frac{1}{4} \hat{u}^2_r + \frac{3}{4} \hat{u}^2_\theta + 2 \frac{c\bar{u}_\theta}{\alpha}\right) \tag{7}$$

$$\hat{V}_2 = \frac{1}{V^2_{rms}}\left\{\left[\frac{J_0(\alpha)}{J_1(\alpha)} - \frac{1}{\alpha}\right]2c\bar{u}_r\right\} \tag{8}$$

Following the procedures of reference 2, the integration indicated in equation (2) is performed by assuming the difference between τ and $\bar{\tau}$ to be negligible to give the atomization rate w'. The in-phase response factor N_R (real part of w' with respect to P') which is defined by

$$N_R = \frac{\int_0^{2\pi} w'P' \, d\omega t}{\int_0^{2\pi} (P')^2 \, d\omega t} \tag{9}$$

is evaluated to first order in $\hat{P}'$. The solution for the in-phase response factor, including the effect of a distributed breakup process described in reference 2, is then

$$N_R = \frac{\sin \sigma\omega\bar{\tau}}{\sigma\omega\bar{\tau}}\left[\frac{\hat{V}_1}{\gamma}\left(\frac{\sin \omega\bar{\tau}}{\omega\bar{\tau}} - \cos \omega\bar{\tau}\right) + \frac{\hat{V}_2}{\gamma}\left(\frac{1 - \cos \omega\bar{\tau}}{\omega\bar{\tau}} - \sin \omega\bar{\tau}\right)\right] \tag{10}$$

where

$$\omega\bar{\tau} = \frac{D\omega}{V_{rms}}\left(\frac{\rho_l}{\bar{\rho}_g} \epsilon\right)^{1/2} \tag{11}$$

The first term within the brackets of equation (10) is identical to that obtained in the previous analysis of reference 2 where the in-phase response was given by

$$N_R = \frac{\sin \sigma\omega\bar{\tau}}{\sigma\omega\bar{\tau}}\left[\frac{\hat{V}_1}{\gamma}\left(\frac{\sin \omega\bar{\tau}}{\omega\bar{\tau}} - \cos \omega\bar{\tau}\right)\right] \tag{12}$$

This converging periodic function with $\omega\bar{\tau}$ (eq. (12)) is shown in figure 2. It characterizes the response for conditions having perturbating particle velocities, steady axial velocity differences, and steady tangential velocities in the absence of steady radial velocities. Changes in steady and acoustic properties affect the value of $\hat{V}_1$ (eq. (7)) and thereby affect the magnitude of the response. The form of the response function, however, is not affected.

A steady radial velocity introduces the second term within the brackets of equation (10). The parameter $\hat{V}_2$ (eq. (8)) is directly proportional to the steady radial velocity. The addition of this second term can appreciably alter the characteristic properties of the response function. The extent of such property changes depends on the magnitude of $\hat{V}_2$ relative to $\hat{V}_1$. Figure 3 shows the response properties for both positive and negative values of $\hat{V}_2$ for the ratio $\hat{V}_2/\hat{V}_1$. In both cases, the response is enhanced; that is, maximum and minimum are increased. The increase in the initial peak value is much larger, however, for positive values (radial flow toward the wall) than for negative values (radial flow toward the center). The increase in peak values is also accompanied by a shift in characteristic time $\omega\overline{\tau}$ at which these peaks occur.

In the subsequent discussion, radial velocities which significantly effect the response function for typical operating conditions are presented. The quantitative effects of steady axial and tangential velocities on the in-phase response factor are also discussed.

DISCUSSION

The analytical solutions for jet dynamics involve a multiplicity of interrelated parameters, and a variety of interpretations relevant to rocket combustor stability could be extracted. The objective of the analysis, however, is to provide some insight into the dominant properties of jet dynamics rather than the intricate effects of an interplay of parameters. In pursuing this objective, precise modeling of jet atomization has been sacrificed to a degree that analytical solutions which retain dominant properties are obtained.

The reliability of the analytical solutions decreases rapidly for characteristic times $\omega\overline{\tau}$ greater than 3π or 4π. With large times the effect of reversing acoustic forces acting on the jet, restraining forces for liquid distortion, and the distributed properties of the breakup process must be considered in greater detail to give quantitatively significant results. Such considerations will decrease the coherency of the jet mass and thereby reduce the response to insignificant levels as $\omega\overline{\tau}$ becomes large.

The response in the region of $\omega\overline{\tau}$ near π radians is relatively insensitive to the model limitations and retains a degree of quantitative significance. The discussion of steady velocity effects on the dynamics of jet atomization, therefore, will be confined to the initial peak value of the in-phase response factor which occurs near an $\omega\overline{\tau}$ of π radians. This peak represents the maximum potential response for most jet conditions and, therefore, the magnitude of this peak implies the probability of unstable combustion being caused by atomization dynamics.

Axial Velocity Difference

The in-phase response factor for jet atomization (eq. (10)) is a function of the axial velocity difference between the liquid jet and surrounding gas. The peak value of the response factor in the absence of any steady radial and tangential velocities is very nearly given by the value of the function at $\omega\overline{\tau}$ equal to π radians:

$$\left(N_R\right)_{max} \simeq \frac{1}{\gamma}\,\hat{V}_1 = \frac{1}{\gamma}\left(\frac{\left|u_l - u_z\right|^2 + \frac{1}{4}\,\hat{u}_r^2 + \frac{3}{4}\,\hat{u}_\theta^2}{\left|u_l - u_z\right|^2 + \frac{1}{2}\,\hat{u}_r^2 + \frac{1}{2}\,\hat{u}_\theta^2}\right) \tag{13}$$

Figure 4 shows the effect of axial velocity difference on peak response at a wall position ($\hat{u}_r = 0$). Increasing the velocity difference decreases the peak response. The effect is pressure amplitude dependent. Large velocity differences are required to cause suppression at high amplitudes. The effect changes with radial position is shown in figure 5 for the radii which divide the cross-sectional area of the chamber into four equal parts. A peak-to-peak pressure amplitude of 10 percent of mean pressure, $\hat{P}' = 0.05$, is used in the comparison (somewhat above the noise level in combustors and a lower limit for realistic mode amplitudes). As shown in figure 5, peak response is relatively unaffected by axial velocity difference near the center. An increase in axial velocity difference, however, is generally suppressive with regard to peak response and potentially more conducive to stable combustion. In effect, high axial velocity differences tend to shield the jet from acoustic oscillations.

Changes in design or operating conditions which would increase the axial velocity difference depend on the specific conditions being altered. For gas-liquid concentric-tube injection, the gas injection velocity can usually be made large relative to the liquid jet velocity and should provide potentially more stable combustion. This has been demonstrated in an extensive study with gaseous hydrogen and liquid oxygen combustors (ref. 8). High hydrogen velocities had a stabilizing affect which could override all other stability variables. For liquid-liquid injection, the liquid injection velocities often exceed the prevailing gas velocity in the atomization zone. With such conditions an increase in the injection velocity or a decrease in the gas velocity by increasing contraction ratio would tend toward higher velocity differences and less potential response. The stabilizing effect of decreasing contraction ratio was also observed in the hydrogen oxygen study (ref. 8). Frequently, however, flows near the injector are either accelerating or decellerating and it is difficult to formulate explicit statements about changes in axial velocity differences. Axial staging, where one propellant is atomized and vaporized more rapidly than the other, adds another variable to axial velocity control which may be useful in establishing large velocity differences for one propellant.

Tangential Velocity

A steady tangential velocity can either increase or decrease the peak response of jet atomization depending on the direction of the steady flow. In the absence of a steady radial flow, the peak response is approximated by

$$\left(N_R\right)_{max} \simeq \frac{1}{\gamma}\hat{V}_1 = \frac{1}{\gamma}\left\{\frac{|u_l - u_z|^2 + \bar{u}_\theta^2 + \frac{1}{4}\hat{u}_r^2 + \frac{3}{4}\hat{u}_\theta^2 + \frac{2c\bar{u}_\theta}{\alpha}}{|u_l - u_z|^2 + \bar{u}_\theta^2 + \frac{1}{2}\hat{u}_r^2 + \frac{1}{2}\hat{u}_\theta^2 + \left[\frac{1}{\gamma}1.72\, J_1(\alpha)P'_w\right]^2 \frac{c\bar{u}_\theta}{\alpha}}\right\} \tag{14}$$

Figure 6 shows the effect of both positive and negative tangential velocities on peak response at a wall position and for an axial velocity difference of 100 feet per second. Positive velocities (in the direction of wave rotation) increase the response, whereas negative velocities (counter to wave rotation) reduce the peak response. Steady velocities as low as 5 feet per second can either double the response factor or reduce it to zero. At higher velocities, extremely large (compared with 1) positive and negative response factors for positive and negative velocities, respectively, are predicted. The effect is similar at all radial positions as shown in figure 7 for the quadripartite area radii and a peak-to-peak pressure amplitude of 10 percent of mean pressure. A steady tangential velocity in the direction of the wave rotation, therefore, is potentially destabilizing and a velocity opposed to the wave rotation is stabilizing with regard to combustor dynamics. It should be noted that the large negative responses at an $\omega\bar{\tau}$ of π are accompanied by positive responses at an $\omega\bar{\tau}$ near 2π. Small negative tangential velocities, however, will give zero response at all values of $\omega\bar{\tau}$.

Self-induced steady tangential velocities in rocket combustors have received little study. Some evidence of vorticity in solid propellant combustors has been observed (ref. 9), as predicted by "acoustic streaming" considerations in acoustic theory. Reference 10, for example, predicts that low order traveling modes should induce a steady wheel flow in a direction opposite to the wave rotation. This would have a stabilizing effect on the atomization process. Such wheel flow will not develop in regions of high Mach number axial flow and little emphasis has been placed on such flow in liquid propellant combustors. These "acoustic streaming" or steady tangential velocities are related to the boundary layer conditions at the wall. Unusual boundary layer conditions created by circumferential slots or acoustic liners in the wall may be expected to affect "acoustic streaming" - especially near the injector where axial Mach number is low or negligible. The development of small steady tangential flows and the effect of slots and liners on such flows should not be neglected considering the extreme sensitivity of jet dynamics to such flows.

The effect of steady tangential velocities (induced by tangential injection of a secondary gas) on jet dynamics and combustion stability has been demonstrated in research combustors (refs. 4 and 5) and analyzed in reference 1. Introducing a tangential velocity by secondary injection, canting of the injection pattern or other means, into an atomization dependent combustor will usually have a destabilizing effect, independent of direction. In a developing acoustic mode, the preferred direction of wave travel is in the direction of giving maximum response. Prolonged steady flow, therefore, will cause a wave motion in the direction of the steady flow. Momentary flow opposed to an established wave, however, may be useful in suppressing instability as discussed in reference 11.

Radial Velocity

As discussed previously and shown in figure 3, a steady radial velocity either toward the wall or toward the center can increase the peak response. An analytical solution at a fixed value of $\omega\bar{\tau}$ cannot be used to express peak values as was the case for axial and tangential velocities. Radial velocities significantly affect the value of $\omega\bar{\tau}$ at which the peaks occur and direct analytical solutions for peak values must be used to examine the response for typical flow conditions.

Figure 8 shows the effect of both positive and negative radial velocities on peak response at a radius of 0.71 (area median radius) and an axial velocity difference of 100 feet per second. Figure 9 shows the effect with radial position. The amplifying effect of radial velocities is most severe at low amplitudes and near the center of the chamber. Flow toward the wall also has a much larger effect than flow toward the center. Flow toward the wall has an effect comparable to that for positive tangential velocities, whereas the increase in response is reduced to about one-third these values for flow toward the center. For both flow directions, however, the increase in peak response in substantial and small radial velocities could significantly alter the stability characteristics of rocket combustors.

Steady radial velocities are not predicted from acoustic theory for "hard wall" cylinders as was the case for tangential velocities. Slots and linear, however, provide "soft wall" conditions which may allow radial velocities to develop - especially for the zero or negligible Mach number flow conditions at the injector face plate. The nonlinear acoustic solutions for such flows have received little attention.

Steady radial velocities can develop in actual rocket combustors from other causes. Recirculation of combustion gases can introduce steady radial flows sweeping across the injector face. An axial-radial recirculation path may be expected whenever a void exists between the injection pattern and the chamber wall. The direction of this flow may be uncertain. Radial flow toward the wall may be expected if combustion occurs close to the injector face (see fig. 10). The opposite flow direction is possible when combustion occurs beyond some critical distance from the injector. Such flow patterns could significantly affect jet response and combustor stability but have received only qualitative attentions as in reference 7.

The influx and discharge of gases from slots and acoustic liners may also be instrumental in creating or affecting radial flow patterns. For example, the flow process for acoustic liners is usually considered to be nonlinear for large pressure amplitudes, as shown in figure 11. Potential flow occurs during influx, but the flow is dissipative with respect to kinetic energy during discharge. The spacial differences in the two flow patterns can cause recirculation of combustion gases during periodic flow and directly affect jet dynamics. This pumping action of acoustic cavities can also modify existing radial flows related to nonuniform mass distribution and other causes and thereby indirectly affect jet behavior. The sensitivity of the atomization process to small radial flows places increased emphasis on design features which affect these previously neglected flow properties.

Nonlinear Instability

The dynamic response of the jet atomization process varies with pressure amplitude and, therefore, provides some insight into the triggering of nonlinear instability in rocket combustors. This was discussed in the previous analysis (ref. 1), but the effect of steady velocities on dynamics provides some additional concepts on nonlinear behavior.

Previously, it was argued that a pressure disturbance reduced the amplitude sensitive characteristic time $\omega\bar{\tau}$, as expressed by equation (11). A disturbance which is sufficiently large to reduce $\omega\bar{\tau}$ to a value less than π (see fig. 2) could trigger instability during the decay of the input disturbance. During decay, $\omega\bar{\tau}$ increases. In-phase response also increases and instability would develop if and when the in-phase response exceeds the acoustic losses of the system.

An input disturbance (bomb or shock with mass addition) which also introduces a steady radial or tangential velocity modifies the concept of triggerable instability. Depending on the direction and magnitude of these steady flows, they may either increase or decrease the probability of sustained instability. A transient flow which enhances the peak in-phase response (radial or in the direction of wave travel) may persist sufficiently long to allow the disturbance to grow rapidly into self-sustained instability by providing a response magnitude which drastically exceeds acoustic losses. Similarly, the probability of instability would be decreased by transient flows which suppress the response.

Circumferential slots and acoustic liners may also generate momentary flow conditions and affect the probability of triggering nonlinear instability. Of particular concern are wall cavities located near the injector. These cavities can be charged with inert or combustible gases by an input disturbance and discharge during the decay period. Both the influx and discharge could create momentary lateral velocities in the low Mach number flow regime near the injector and affect the stability rating. This behavior may contribute to the stabilizing affects obtained from slots and liners during stability testing.

CONCLUDING REMARKS

This analysis of jet atomization shows that steady low-level radial and tangential velocities could significantly affect the stability of rocket engine combustors. The significance of steady velocity on stability, however, is not limited to jet atomization. Most atomization processes (impinging jets, spray nozzles, etc.) are dependent on aerodynamic factors in a manner similar to that for jet atomization. Although the analyses for other atomization methods is more complex than for jets, the dependence on aerodynamic forces would give a dynamic response similar to that for jets.

Accepting the validity of the jet analysis and its qualitative adaptation to most injection methods places increased importance on low-level lateral gas flow in the region of the injector. Some sources of lateral flow were postulated and discussed in this report. These and others must be more fully explored with regard to the magnitude, and the parameters affecting lateral flow before the relevance of steady flow effects to actual combustors can be established.

Some studies of lateral flow behavior which could influence the design concepts for stable rocket combustors are:

(1) "Acoustic streaming" velocities for "soft," dissipative and irregular walls with emphasis on boundary layer variables that enhance tangential and radial velocities which suppress atomization response

(2) Lateral and axial mass distribution effects on lateral and recirculation velocities with emphasis on near-uniform mass distribution rather than isolated sources

(3) Influence of acoustic liners, slots, and cavities on lateral and recirculation velocities caused by mass distribution effects under dynamic conditions

(4) Transient lateral velocities caused by slow discharge of abruptly charged wall cavities with attention on the probability and consequences of charging with combustible mixtures

(5) Lateral velocities for combustion chambers with minor deviations from cylindrical geometry such as concave and convex injector faces, tapered, and contoured chamber walls

(6) Steady flow patterns in combustion chambers with baffles and surface protrusions

SUMMARY OF RESULTS

The analysis of steady velocities effects on the the dynamic response of jet atomization in traveling transverse acoustic modes has shown the following with regard to the peak in-phase response to pressure oscillations:

1. High axial velocity differences between the liquid and surrounding gas suppress the response.
2. A steady tangential velocity in the direction of the acoustic wave rotation increases the response, and a counterwave velocity suppresses the response.
3. A steady radial velocity increases the response with flow toward the wall giving about three times the increase obtained from flow toward the center.
4. The sensitivity of response to tangential and radial velocities is sufficiently large to be of concern with regard to velocities caused by nonuniform propellant distribution, "acoustic streaming," and acoustic damping devices in actual combustors.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 25, 1969,
128-31.

APPENDIX - SYMBOLS

c speed of sound, ft/sec

D jet diameter, ft

J_n Bessel function of first kind of order n

N_R response factor, real or in-phase component of w'/P', dimensionless

P pressure, lb/ft^2

r radial position, dimensionless

t time, sec

u velocity, ft/sec

V magnitude of relative velocity vector, ft/sec

$\hat{V}_1, \hat{V}_2$ parameters defined by eqs. (7) and (8)

w mass flow rate, lbm/sec

α radius parameter, 1.841 r

γ ratio of specific heats

ϵ critical value of relative distortion, δ/D

δ jet distortion, ft

ω frequency, rad/sec

θ phase angle, rad

ρ density, lb/ft^3

σ instantaneous deviation of τ from mean

τ jet breakup time, sec

Subscripts:

g gas

l liquid

r radial component

rms root mean square

z axial component

θ angular component

w wall

Superscripts:

$(\bar{\ })$ mean or average value

$(\hat{\ })$ maximum value

$(\ )'$ perturbation about mean

REFERENCES

1. Heidmann, Marcus F.; and Groeneweg, John F.: Analysis of the Dynamic Response of Liquid Jet Atomization to Acoustic Oscillations. NASA TN D-5339, 1969.

2. Heidmann, M. F.; and Groeneweg, J. F.: Dynamic Behavior of Liquid Jet Atomization. Fifth ICRPG Combustion Conference. Rep. CPIA Publ. No. 183, Applied Phys. Lab., Johns Hopkins Univ., Dec. 1968, pp. 111-117.

3. Clark, Bruce J.: Breakup of a Liquid Jet in a Transverse Flow of Gas. NASA TN D-2424, 1964.

4. Heidmann, Marcus F.: Oscillatory Combustion of a Liquid-Oxygen Jet with Gaseous Hydrogen. NASA TN D-2753, 1965.

5. Burrows, Marshall C.: Dynamic Response of Hydrazine-Nitrogen Tetroxide Combustion to Transverse Gas Flow. NASA TN D-4984, 1969.

6. Combs, L. P.; Hoehn, F. W.; and Webb, S. R.: Combustion Stability Rating Techniques. Rep. R-6355-4, Rocketdyne Div., North American Aviation, Inc. (AFRPL-TR-66-229, DDC No. AD-801897), Sept. 1966.

7. Coultas, T. A.: Radial Winds. Fifth ICRPG Combustion Conference. Rep. CPIA Publ. No. 183, Applied Phys. Lab., Johns Hopkins Univ., Dec. 1968, pp. 127-132.

8. Conrad, E. William; Bloomer, Harry E.; Wanhainen, John P.; and Vincent, David W.: Interim Summary of Liquid Rocket Acoustic-Mode-Instability Studies at a Nominal Thrust of 20 000 Pounds. NASA TN D-4968, 1968.

9. Swithenbank, J.; and Sotter, J. G.: Vorticity in Solid Propellant Rocket Motors. Propulsion and Power in Space. Vol. 1 of the Proceedings of the XIVth International Astronautical Congress. Edmond Brun and Irwin Hersey, eds., Gauthier-Villars, Paris, 1965, pp. 249-275.

10. Maslen, Stephen H.; and Moore, Franklin K.: On Strong Transverse Waves Without Shocks in a Circular Cylinder. J. Aeron. Sci., vol. 23, no. 6, June 1956, pp. 583-593.

11. Heidmann, Marcus F.; and Feiler, Charles E.: Evaluation of Tangential Velocity Effects on Spinning Transverse Combustion Instability. NASA TN D-3406, 1966.

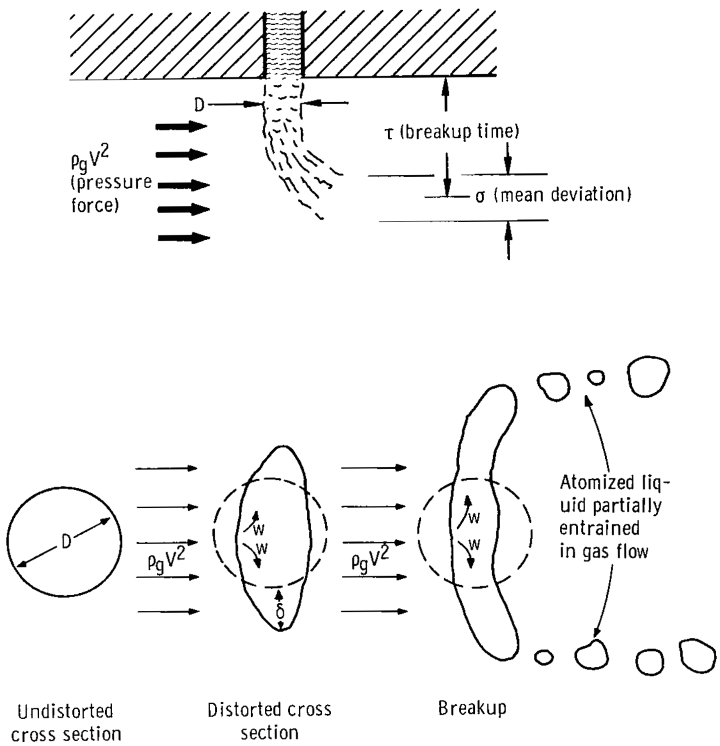

Figure 1. - Jet atomization model.

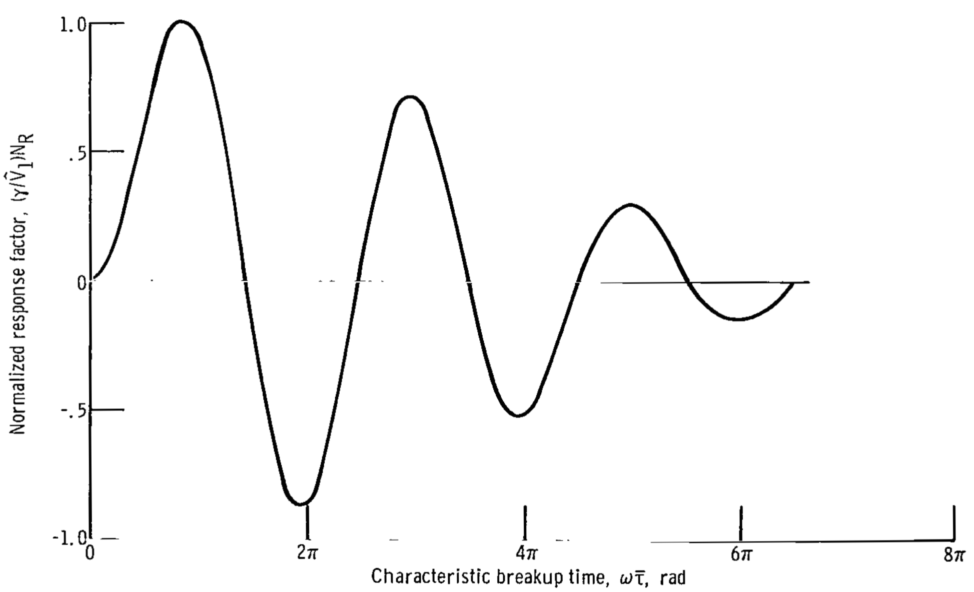

Figure 2. - Response function for conditions with no steady radial velocity.

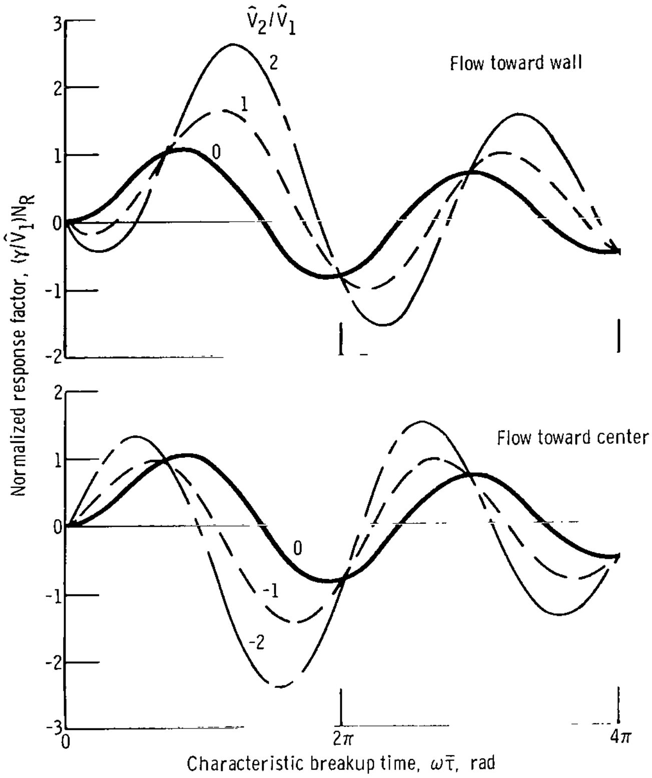

Figure 3. - Response function for conditions with steady radial velocities.

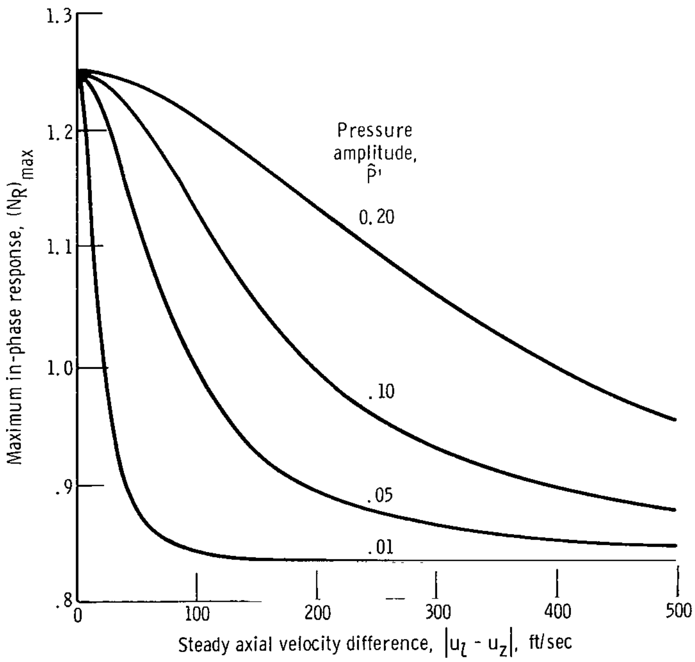

Figure 4. - Steady axial velocity-difference effect on response with pressure amplitude. Radius, 1.0; speed of sound, 5000 feet per second; ratio of specific heats, 1.2.

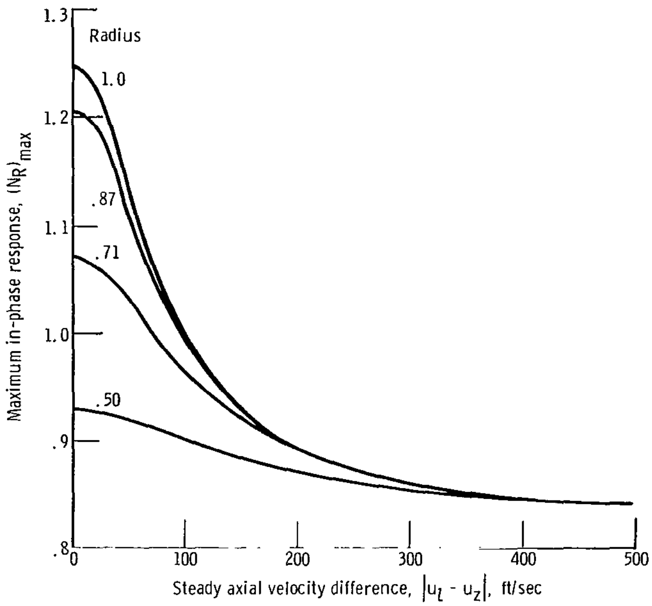

Figure 5. - Steady axial velocity-difference effect on response with radial position. Pressure amplitude, 0.05; speed of sound, 5000 feet per second; ratio of specific heats, 1.2.

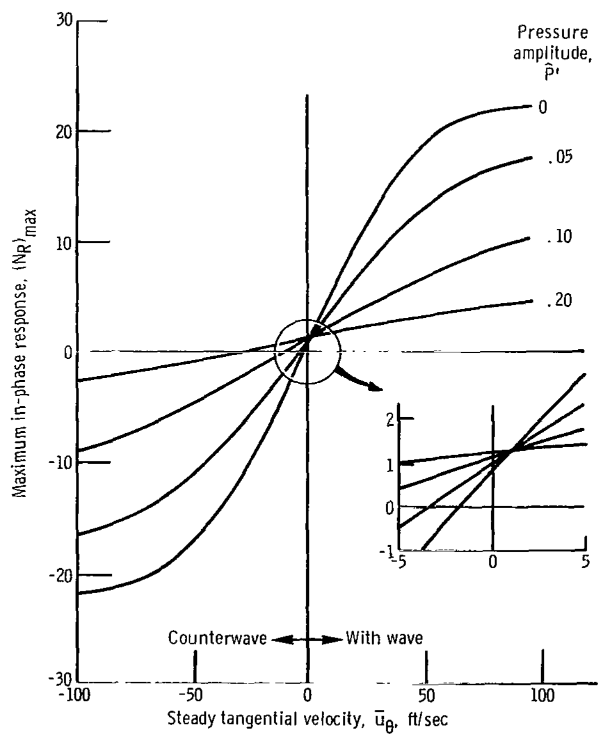

Figure 6. - Steady tangential velocity effect on response with pressure amplitude. Radius, 1.0; $|u_l - u_z|$, 100 feet per second; speed of sound, 5000 feet per second; ratio of specific heats, 1.2.

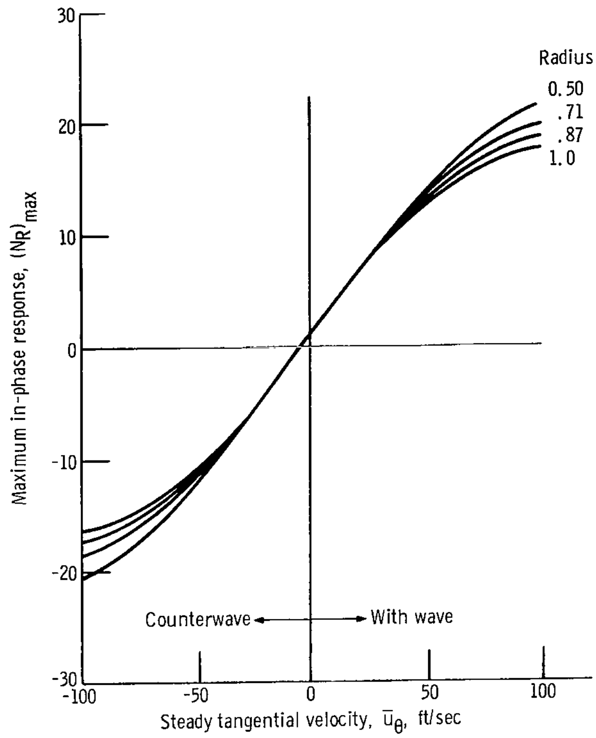

Figure 7. - Steady tangential velocity effect on response with radial position. Pressure amplitude, 0.05; $|u_l - u_z|$, 100 feet per second; speed of sound, 5000 feet per second; ratio of specific heats, 1.2.

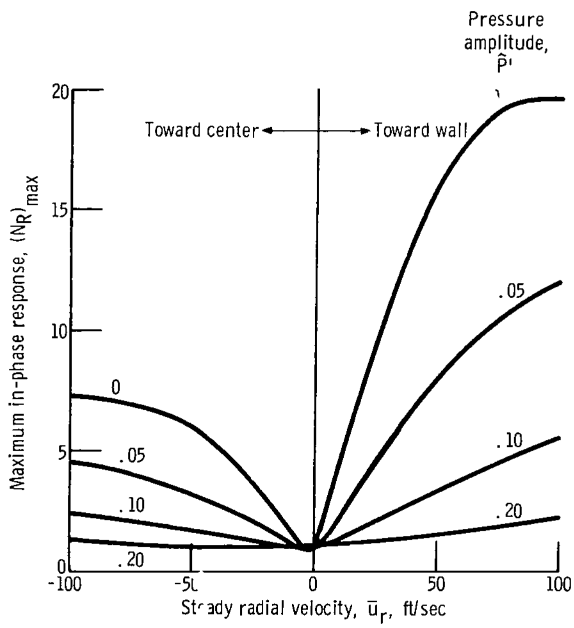

Figure 8. - Effect of radial velocity on response with amplitude. Radius, 0.71 (area median); $|u_l - u_z|$, 100 feet per second; speed of sound, 5000 feet per second; ratio of specific heats, 1.2.

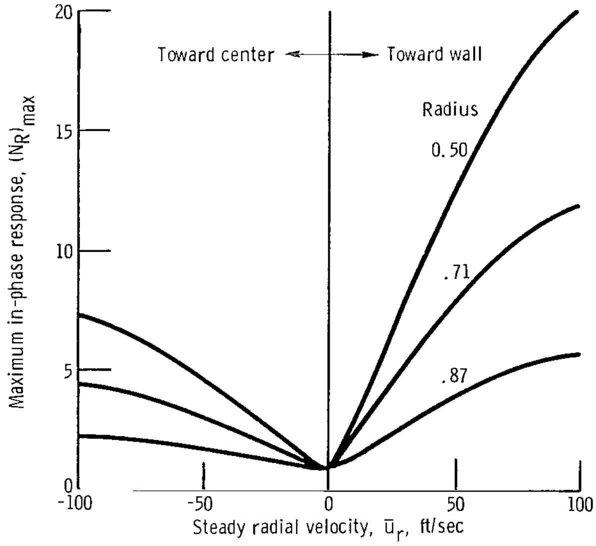

Figure 9. - Effect of radial velocity on response with radial position. ΔP_{p-p}, 10 percent; $|u_l - u_z|$, 100 feet per second; speed of sound, 5000 feet per second; ratio of specific heats, 1.2.

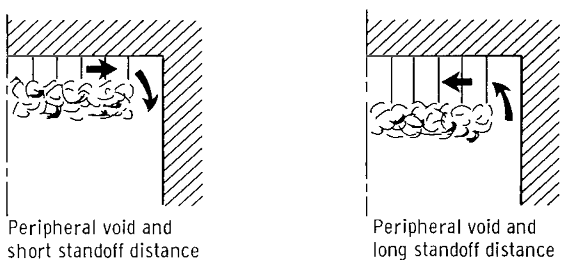

Figure 10. - Radial winds from mass distribution effects.

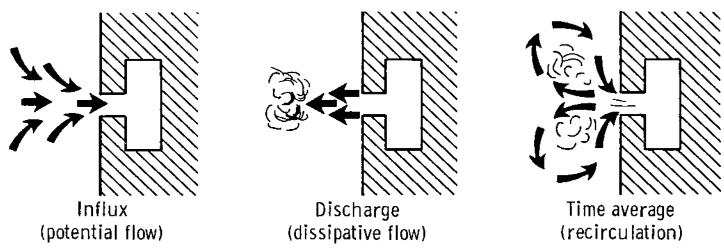

Figure 11. - Recirculation from nonlinear cavity flow processes.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

051 001 37 51 3CS 69321 00903
AIR FORCE WEAPONS LABORATORY/WLIL/
KIRTLAND AIR FORCE BASE, NEW MEXICO 8711

[illegible] CHIEF, TECH. LIBRARY

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546