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Experimental Validation of Force Radiation Modes: A Novel Approach to Reduction of Sound Radiation from Vibrating Structure

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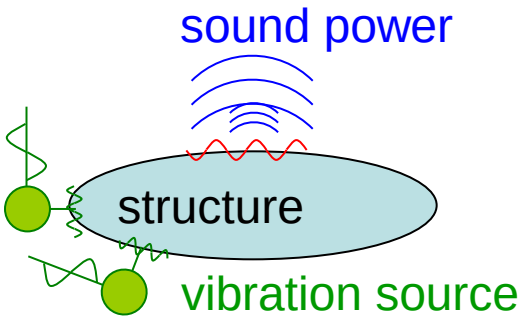
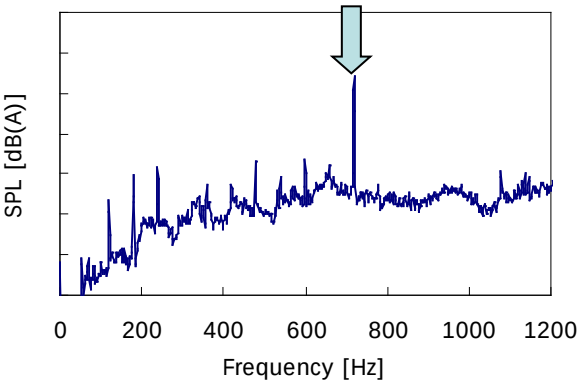
Introduction

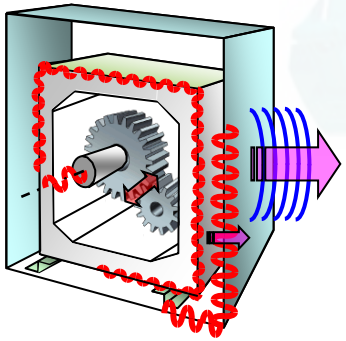
Structure borne sound from machinery.

- Radiated acoustic power is affected by locations of vibration sources (i.e. driving force location)



especially pure tone noise →





Eg. pulsation noise, gear or motor noise etc.

Identify the vibration source location which minimize the radiated sound

Introduction

To minimize the radiated sound...

vibration modal analysis are often applied

However...

vibration reduction does not always reduce radiated sound

[1] Tanaka, et al, JSME,C , 66(648) , 106-112 , 1991
[2] Pan, J., et al, J. Acoust. Soc. Am., 91(4), 2056-2066, 1992

It is necessary to consider not only vibration but also radiated sound.

Radiation Modes

Radiation Modes

- Developed in the field of ANC (1990s -)

[3] N. Tanaka, Y Uchino, Transactions of the JSME, Series C，66(648)，106-112，200.
[4] S. J. Elliot, et al., J. Acoust. Soc. Am, 94(4), 2194-2204, 1993.

- depend only on the geometry
- independent of a structure's surface vibratio

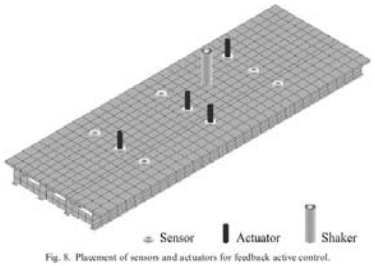


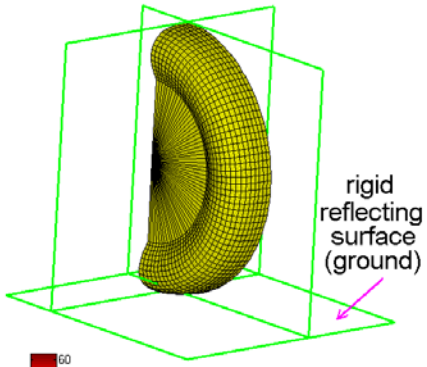
Fig. 8. Placement of sensors and actuators for feedback active control.

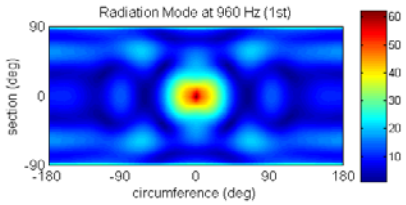
Powerful tool for interpreting sound radiation

- Application to practical subjects
  - low-frequency noise from a highway bridge
  - tire/road interaction noise

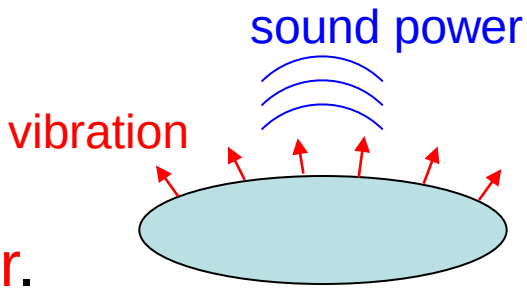
[5]T. Chanpheng, et al., Applied Acoustics, 65, 109-123, 2004.
[6]K. Yum, J. S. Bolton, Noise-Con 2004.

etc.





Objective



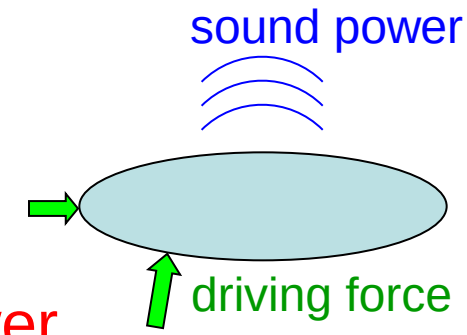
Radiation modes

- vibration distribution and acoustic power.

Previously

Extended radiation modes
(f_{rad}-mode: force radiation mode)

- driving force distribution and acoustic power



⇨ Verified the usefulness of the new modes by simulation

Objective of this study

To verify the usefulness of the extended radiation mode by experiment

Radiation Modes

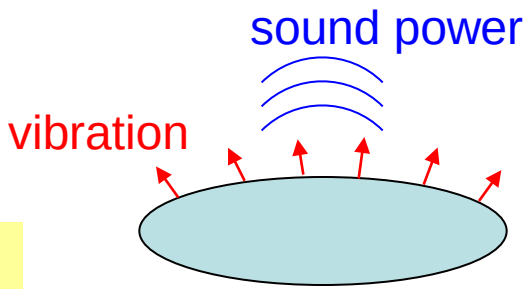
sound power

acoustic transfer vector

$$W = \frac{S}{2N}\mathrm{Re}\left\{ \mathbf{v}_e^{\mathrm{H}}\mathbf{p}_e \right\} = \frac{S}{2N}\mathrm{Re}\left\{ \mathbf{v}_e^{\mathrm{H}}\mathbf{Z}_e\mathbf{v}_e \right\}$$

vibration velocities of the structure

sound pressure on the surface



$$= \mathbf{v}_e^{\mathrm{H}}\mathbf{R}\mathbf{v}_e$$

Radiation resistance matrix

eigenvalue/eigenvector decomposition

$$\mathbf{R} = \mathbf{Q}^{\mathrm{T}}\boldsymbol{\Lambda}\mathbf{Q}$$

Eigenvalue

Eigenvector

⇩

Radiation Modes

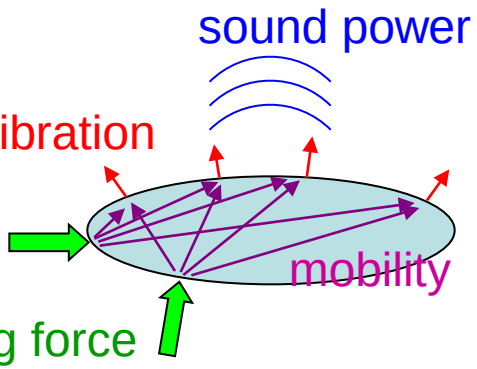
Force Radiation Modes (f_{rad}-mode)

vibration velocities on the boundary

$$\mathbf{v}_e = \mathbf{T}\mathbf{f}_e$$

Mobility of structure

Driving force



$$W = \mathbf{v}_e^{\mathrm{H}}\mathbf{R}\mathbf{v}_e = \mathbf{f}_e^{\mathrm{H}}\mathbf{T}^{\mathrm{H}}\mathbf{R}\mathbf{T}\mathbf{f}_e = \mathbf{f}_e^{\mathrm{H}}\mathbf{C}\mathbf{f}_e$$

eigenvalue/eigenvector decomposition

Eigenvalue

$$\mathbf{C} = \mathbf{M}^{\mathrm{T}}\mathbf{\Phi}\mathbf{M}$$

Eigenvector

Force Radiation Modes (f_{rad}-mode)

$$\mathbf{C} = \mathbf{M}^{\mathrm{T}} \mathbf{\Phi} \mathbf{M}$$

Eigenvalue

Eigenvector: Force Radiation mode

$$\mathbf{\Phi} = \begin{bmatrix} \phi_1 & & 0 \\ & \phi_2 & \\ & & \ddots \\ 0 & & \phi_n \end{bmatrix}$$

1st

2nd

$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & & \vdots \\ \vdots & & \ddots & \\ m_{n1} & \cdots & & m_{nn} \end{bmatrix}$$

1st

2nd

Force Radiation Modes (f_{rad}-mode)

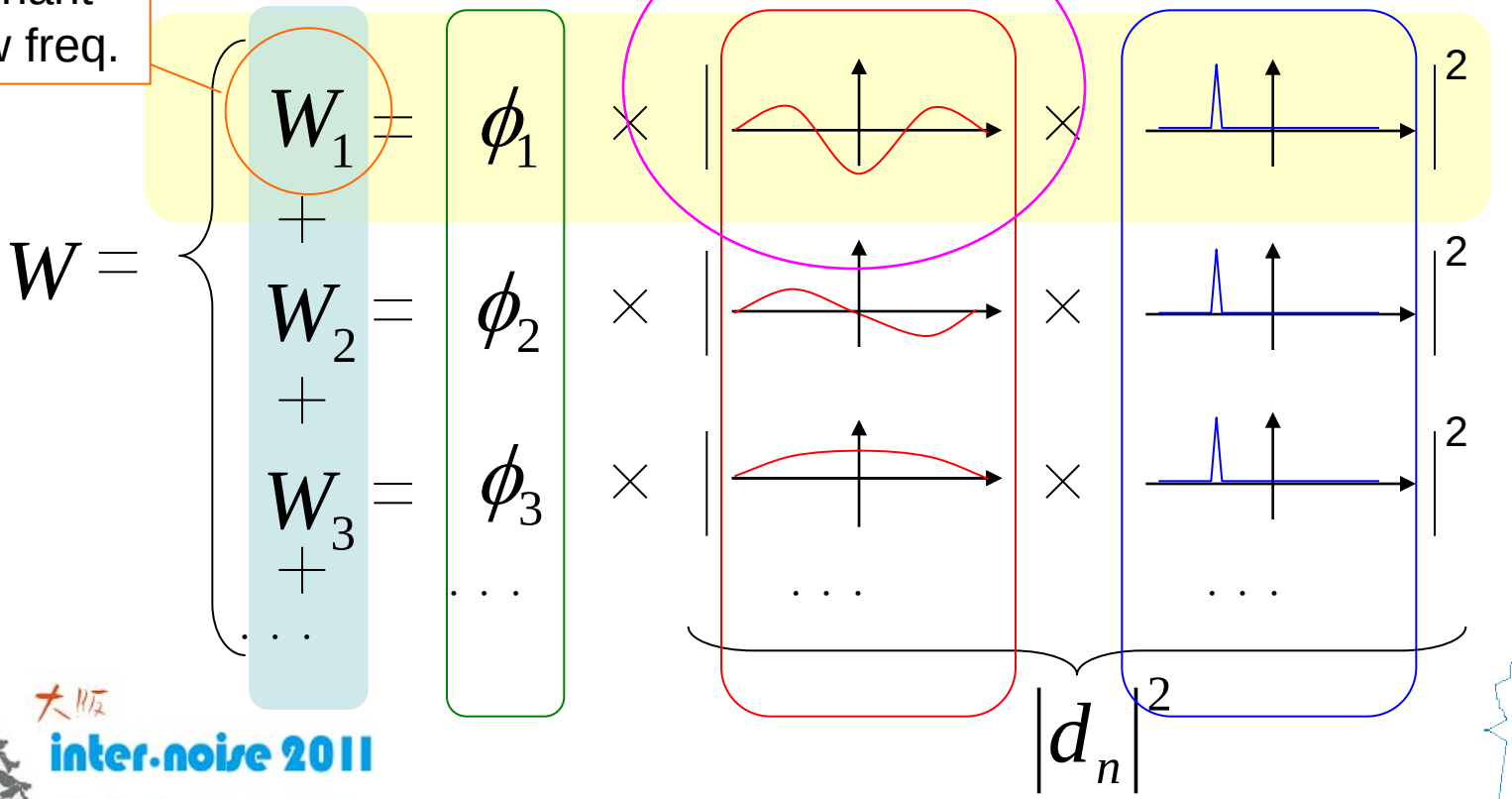
$$W = \mathbf{f}_e^{\mathrm{H}}\mathbf{M}^{\mathrm{T}}\mathbf{\Phi}\mathbf{M}\mathbf{f}_e = \mathbf{d}^{\mathrm{H}}\mathbf{\Phi}\mathbf{d} = \sum_{n=1}^{N} W_n = \sum_{n=1}^{N} \phi_n \left| d_n \right|^2$$

Dominant in low freq.

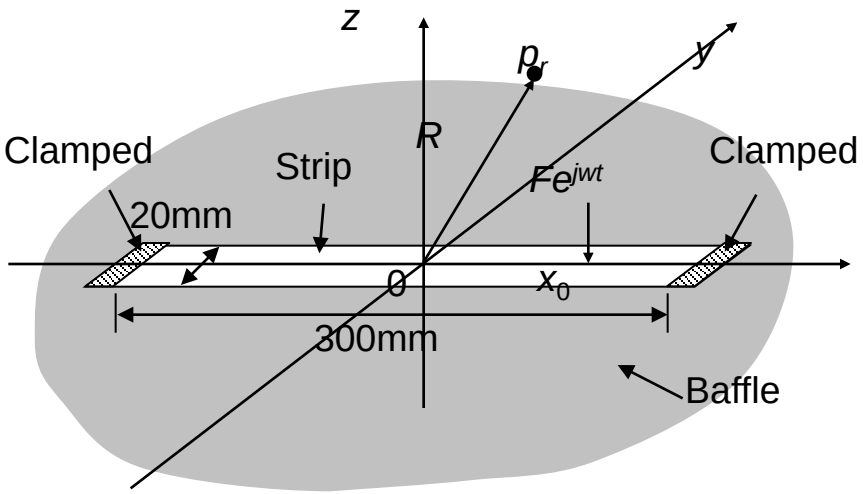
Eigenvalue

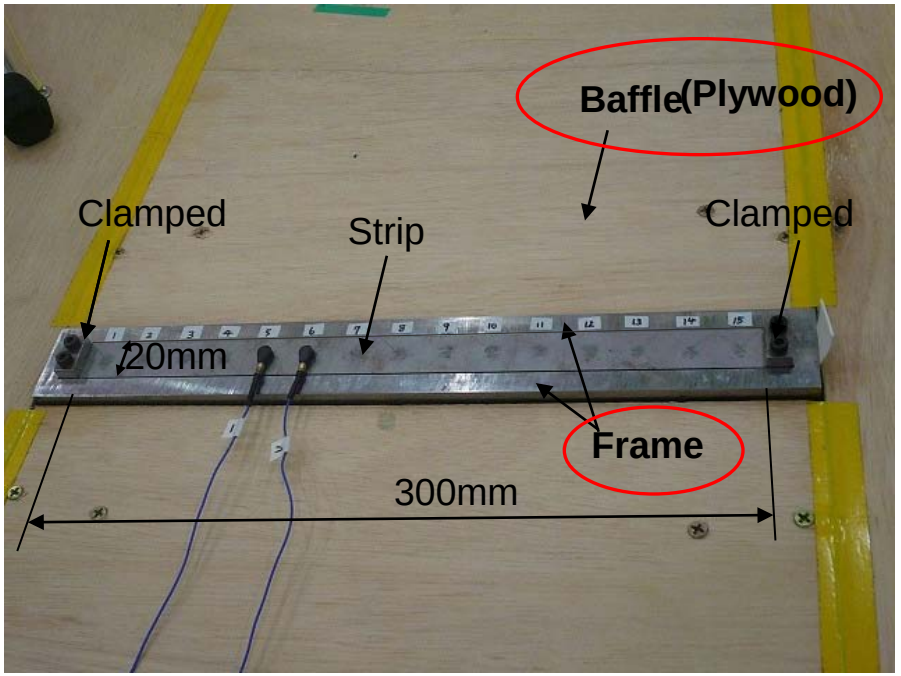
frad-modes

Driving force



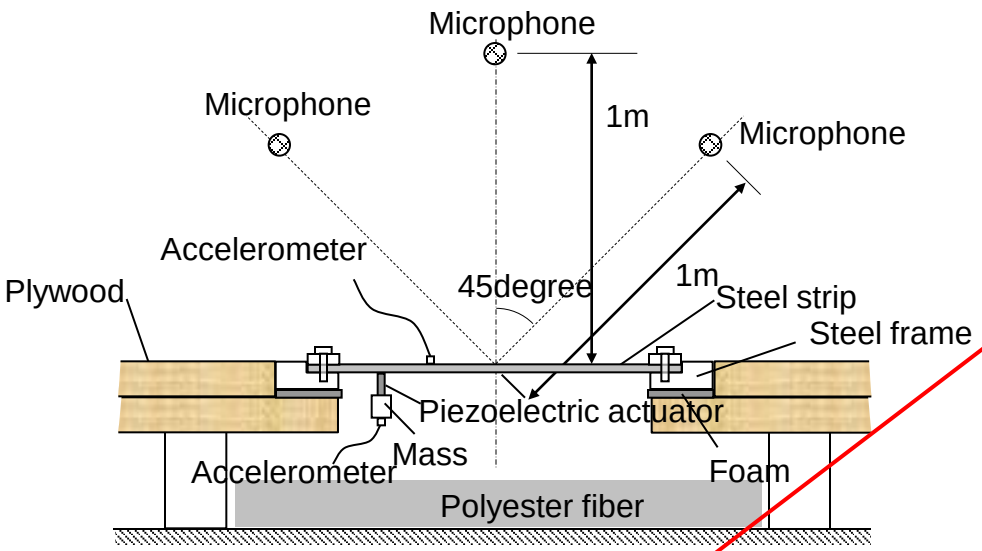
Experiment -Vibration object

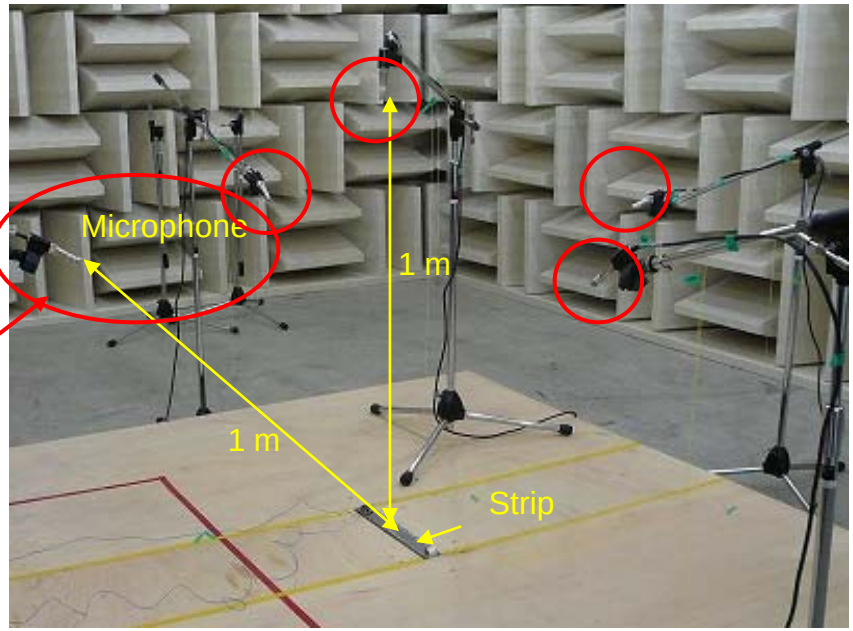




- The strip was held in a steel frame and was surrounded by a baffle.
- Thickness: 1 mm, width: 20 mm, length: 300 mm.
- Divided into 15 elements of equal length.
- Driven by the piezoelectric actuator.

Experiment - Sound power

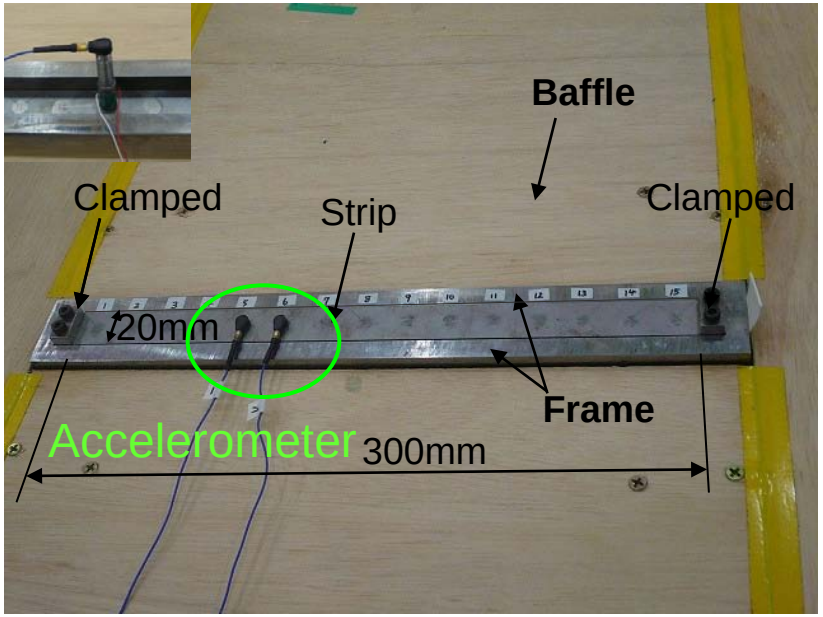


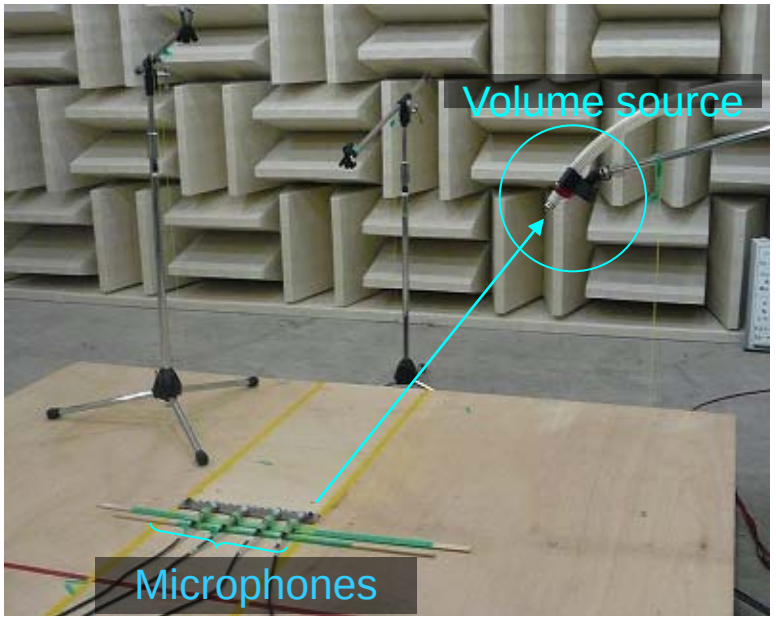


$$W = \sum_{r=1}^{R} \frac{|p_r|^2}{2\rho c} S_r$$

- Sound pressure was measured at five points
- 1 m distant from the center of the strip

Experiment - Force radiation modes





Mobility

Acoustic Transfer Vector (ATV)

$$W = \sum_{r=1}^{R} \frac{\mathbf{f}_e^{\mathrm{H}} \mathbf{T}_e^{\mathrm{H}} \mathbf{Z}_r^{\mathrm{H}} \mathbf{Z}_r \mathbf{T}_e \mathbf{f}_e}{2\rho c} S_r = \mathbf{f}_e^{\mathrm{H}} \mathbf{M}^{\mathrm{H}} \mathbf{\Phi} \mathbf{M} \mathbf{f}_e$$

f_{rad}-modes

The acoustic transfer functions were measured reciprocally

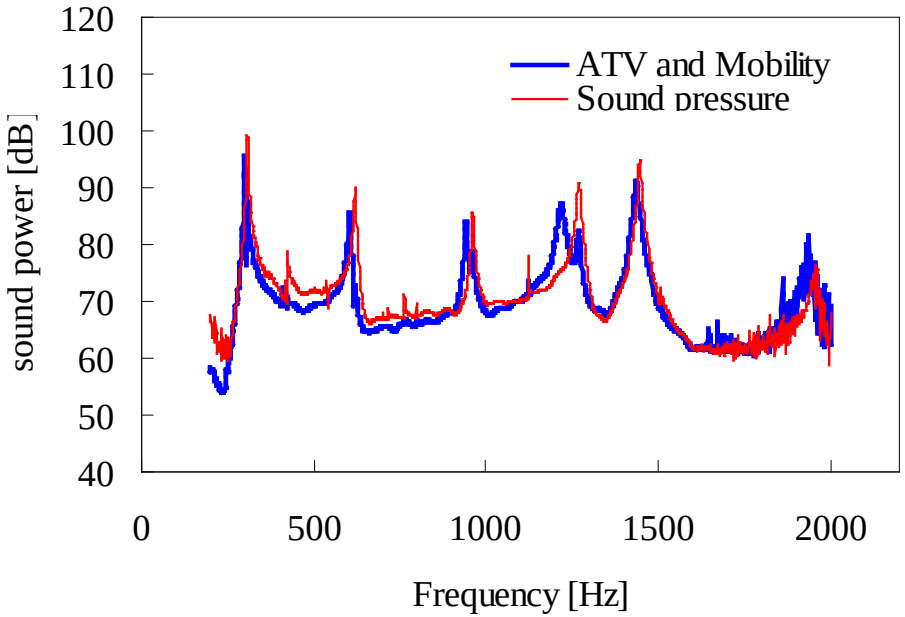
Validation of the experimental data

Sound pressure

$$W = \sum_{r=1}^{R} \frac{|p_r|^2}{2\rho c} S_r$$

ATV and Mobility

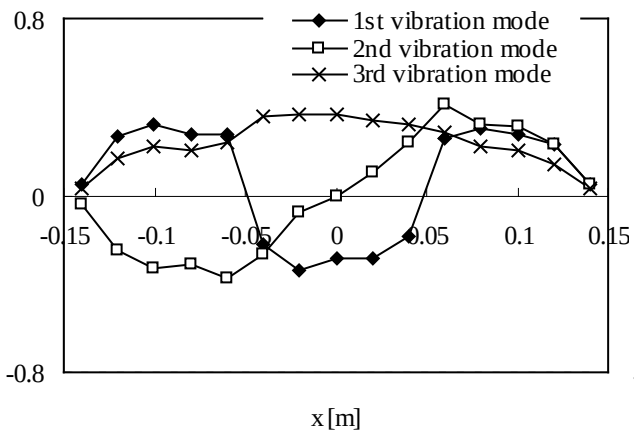
$$W = \sum_{r=1}^{R} \frac{\mathbf{f}_e^{\mathrm{H}} \mathbf{T}_e^{\mathrm{H}} \mathbf{Z}_r^{\mathrm{H}} \mathbf{Z}_r \mathbf{T}_e \mathbf{f}_e}{2\rho c} S_r$$

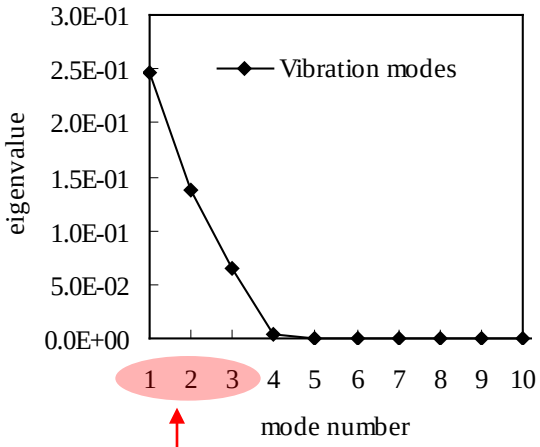


The mobility and the acoustic transfer functions were measured accurately

Modes at 250 Hz

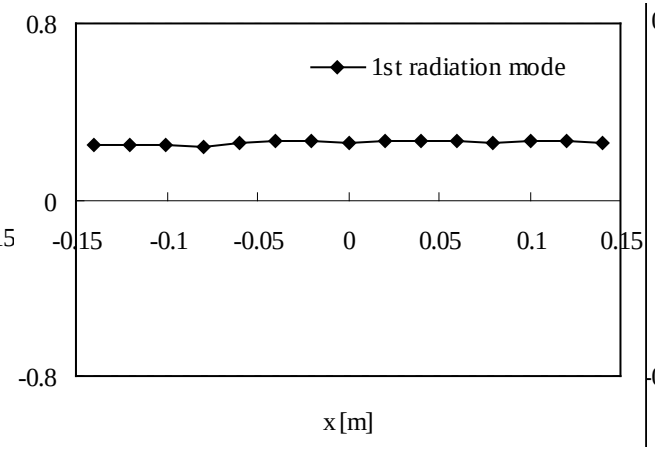
Vibration modes

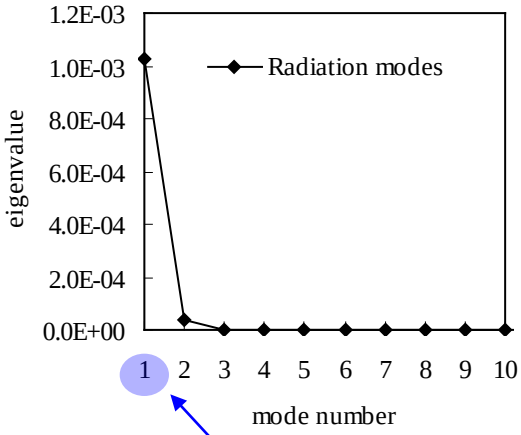




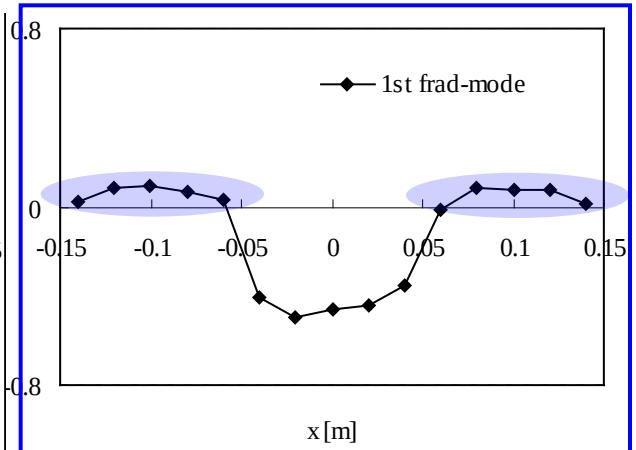
High contribution to the average mean square vibration velocity

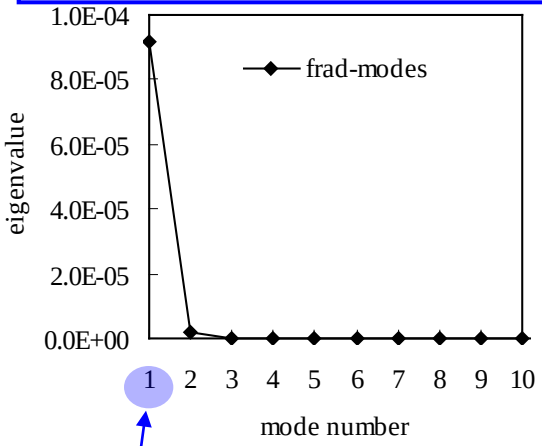
Radiation mode





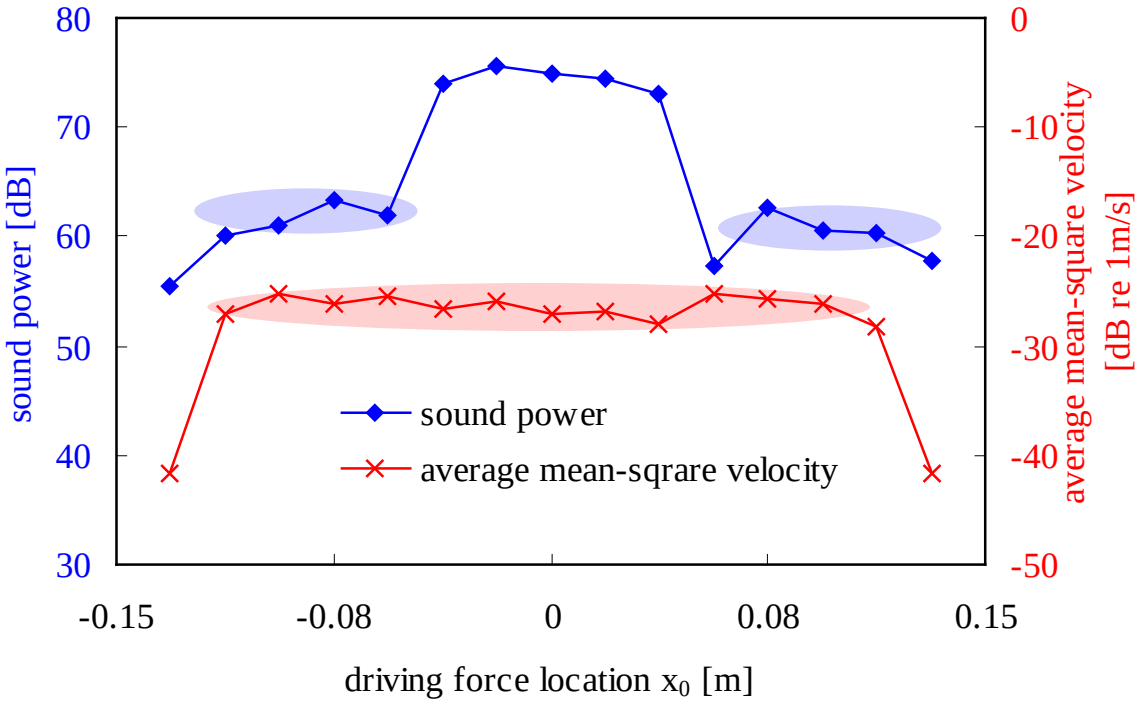
Force radiation mode

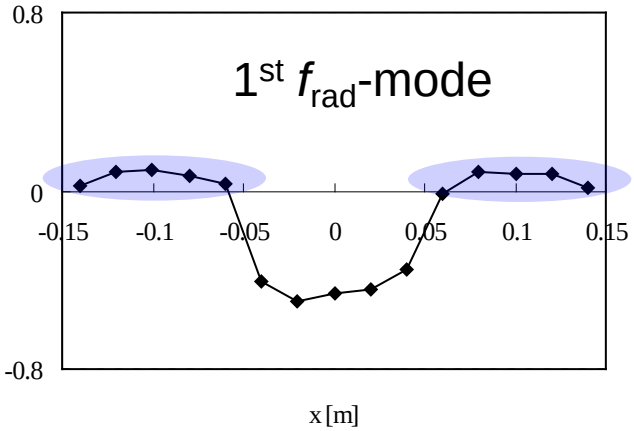




High contribution to the sound power

Result at 250 Hz





The f_{rad}-modes obtained directly from measured data can provide useful guidance regarding the driving force locations that result in the minimum sound radiation.

You can't tell from the vibration modes

Conclusion

The acoustic transfer functions and the mobility of a steel strip were measured to calculate force radiation modes directly.

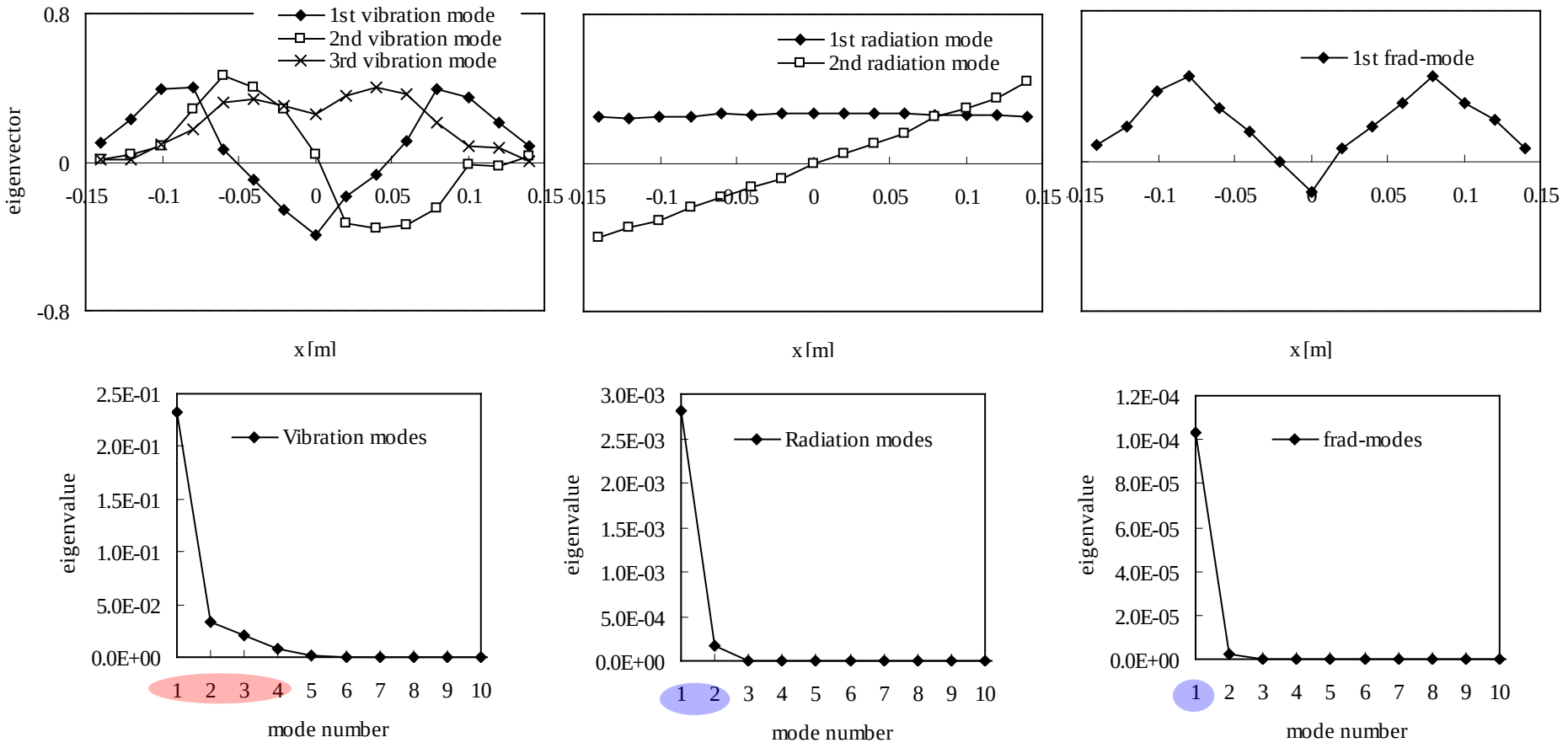
- Force radiation modes were identified accurately
- Useful to find the location which minimize the sound power in low frequency.

Future work

- Application to practical subjects

Thank you.

Modes at 350 Hz



Result at 350 Hz