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ON THE MODELING OF ARTIFICIAL PROPELLER NOISE

By

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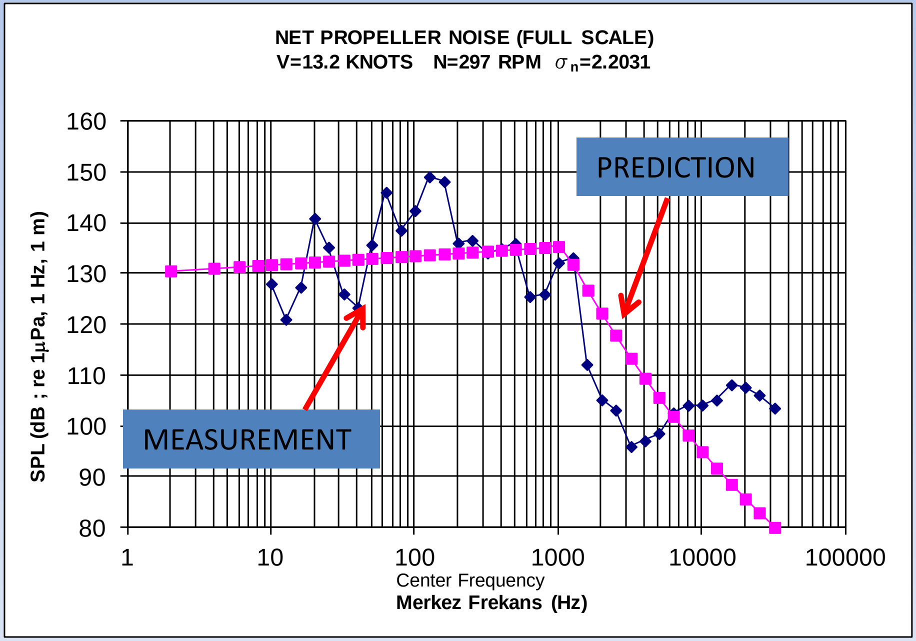
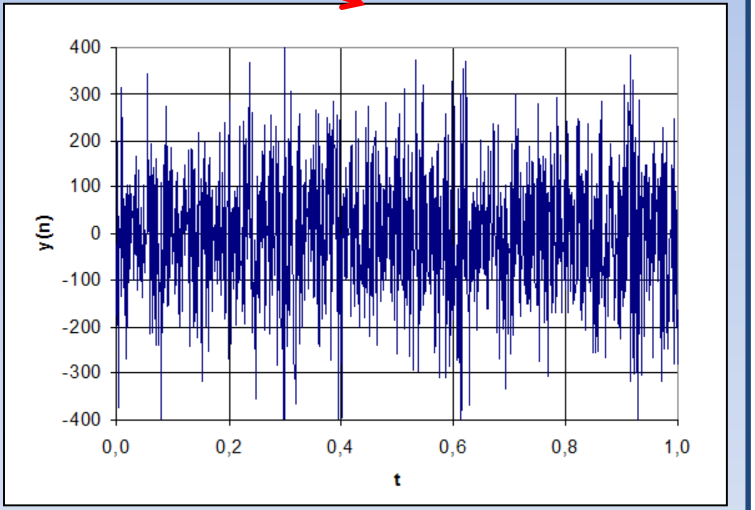
- An *empirical prediction* model of broadband noise and *its modulation* in the time domain for marine propellers is proposed.



NET PROPELLER NOISE (FULL SCALE)
V=13.2 KNOTS N=297 RPM σ_n=2.2031

PREDICTION

MEASUREMENT



Why did we need such a study ?

All referees who reviewed the papers asked the same question !!!

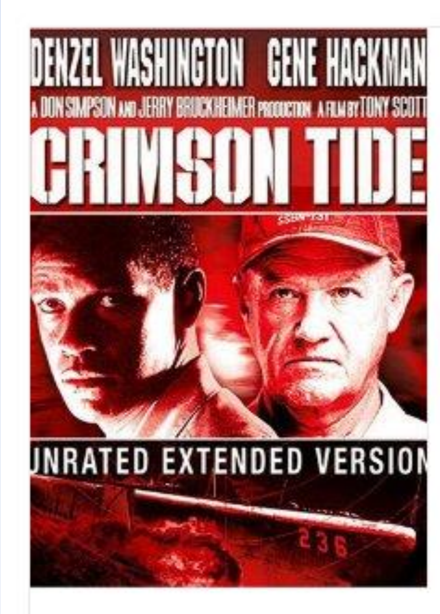
- For use in a sonar training simulator being developed by TUBITAK to train navy sonar personnel.

- The simulator includes all aspects of sonar operation, with emphasis on training in:
  - weak target detection in the presence of noise & reverberation (echo)
  - torpedo detection
  - audio listening
  - classification

Remember that the movie

Crimson Tide

in 1995.



- There was a hot pursuit between American submarine **USS Alabama** and Soviet **Akula Class** submarine .....

Гвардейская ПЛА пр.971 "Гепард" возвращается с госиспытаний.
Белое море. Июль 2001 года. Фото: В. Уткин.

- How could the crew of Alabama identify the class of the Akula Class submarine ?????

Ans: From the noise signature of the submarine?

Real sounds may be composed of many sources. E.g. propeller, body, machinery and also natural sounds (rain, surface wind, etc...)

In that context, propeller noise has been modeled in this study. The propeller noises were then embedded into the simulator noise database.

Why is this study interesting?

It is the result of co-operation of two far different disciplines which are

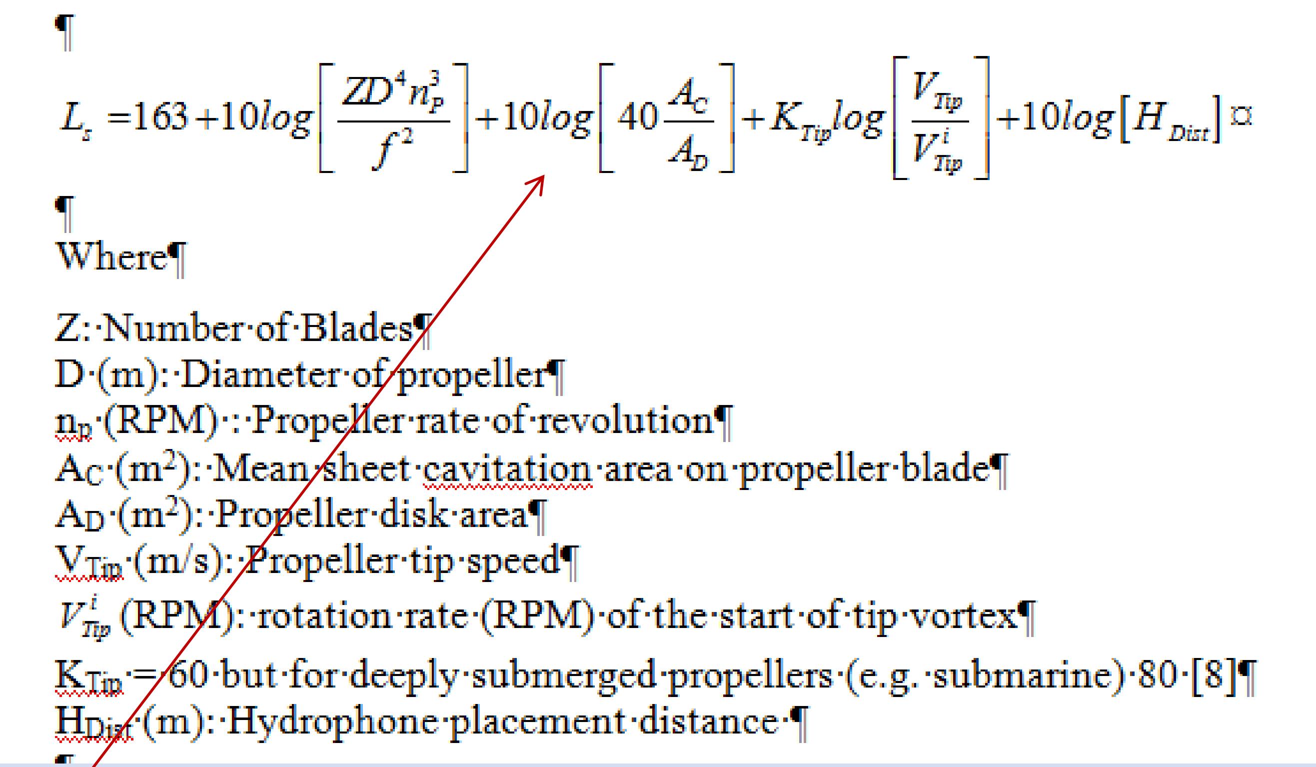
- Naval Architecture
- Electronic Engineering

Part I: Prediction

- The prediction of broadband noise radiated from a marine propeller using empirical models is a more common approach.
- These works are based on relationships similar to those used in Brown ’s semi empirical relation.
- A difficulty encountered in propeller noise prediction is the limited experimental, particularly full scale measurement data available in the open literature.
- A study [5] which includes cavitation tunnel measurements as well as full scale measured data is quite valuable in this sense.

- The primary source of propeller noise is cavitation noise generated as the propeller operates in the non-uniform wake field.
- The cavitation is generally composed of tip vortex and sheet cavitation.
- Bubble cavitation may be seen which may additionally increase the level of noise considerably.
- Accurate prediction of propeller cavitation in a non uniform wake field can provide a good basis upon which to predict over-all propeller noise.

- Cavitation analysis is made by a LSM algorithm together with the prediction of the total hydrodynamic performance.
- It can be conceptualized that the model propeller is to be tested in a cavitation tunnel.
- A semi empirical model, the broadband noise spectrum of the model propeller may be calculated.
- Adjustments may then be applied to the broadband noise spectrum to scale the results up to that of the full size propeller.



$$L_s = 163 + 10log\left[\frac{ZD^4 n_P^3}{f^2}\right] + 10log\left[40\frac{A_C}{A_D}\right] + K_{Tip}log\left[\frac{V_{Tip}}{V_{Tip}^i}\right] + 10log\left[H_{Dist}\right]$$

Where

Z: Number of Blades
D (m): Diameter of propeller
n_p (RPM) : Propeller rate of revolution
A_C (m^2): Mean sheet cavitation area on propeller blade
A_D (m^2): Propeller disk area
V_{Tip} (m/s): Propeller tip speed
V_{Tip}^i (RPM): rotation rate (RPM) of the start of tip vortex
K_{Tip} = 60 but for deeply submerged propellers (e.g. submarine) 80 [8]
H_{Dist} (m): Hydrophone placement distance

Eq is valid for peak freq fp<10kHz

Peak frequency

$$f_p = \frac{4400}{D}\left(\frac{\sigma_n^i}{\sigma_n}\right)^{-3.2/2}\left(\frac{P_s}{22}\right)^{1/3} \quad => \left(\frac{\sigma_n^i}{\sigma_n}\right)^{1/2} < 1.7$$

$$f_p = \frac{1100}{D}\left(\frac{\sigma_n^i}{\sigma_n}\right)^{-2.0/6}\left(\frac{P_s}{22}\right)^{1/3} \quad => \left(\frac{\sigma_n^i}{\sigma_n}\right)^{1/2} \geq 1.7$$

$$\sigma_n = \frac{P_s - P_V}{\frac{1}{2}\rho n_p^2 D^2}$$

$$\frac{A_C}{A_D} = \left[\left(\frac{\sigma_n^i}{\sigma_n}\right)^{1/2} - 1\right]^2 \left(\frac{\sigma_n^i}{\sigma_n}\right)^{-1}$$

Sound pressure level

$$L_s = A\, f^{0.007} \quad => f < f_p$$

$$L_s = B\, f^{-0.2} \quad => f > f_p$$

constants A and B are determined from the continuity characteristics of the noise spectrum

$$A = \left(\frac{L_{s_p}}{f_p}\right)^{0.007} ;\ B = \left(\frac{L_{s_p}}{f_p}\right)^{-0.2}$$

- The increase in the noise level in moving from model to full scale is given by (ITTC scaling)

$$\Delta L_{(P)} = 20\log\left[\left(\frac{D_P}{D_M}\right)^{z}\left(\frac{r_M}{r_P}\right)^{x}\left(\frac{\sigma_P}{\sigma_M}\right)^{y/2}\left(\frac{n_P D_P}{n_M D_M}\right)^{y}\left(\frac{\rho_P}{\rho_M}\right)^{y/2}\right] dB$$

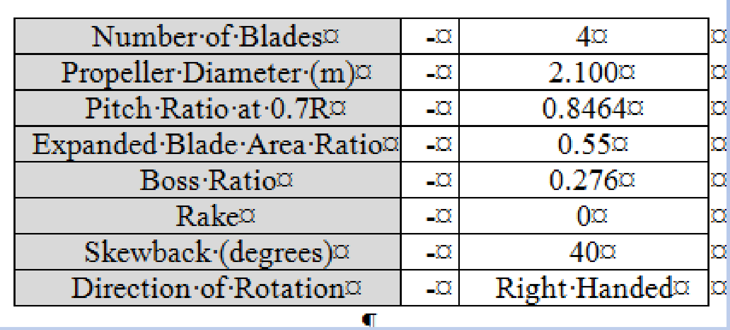
- frequency shift is expressed a $\frac{f_P}{f_M} = \frac{n_P}{n_M}$

- the increase in the noise level

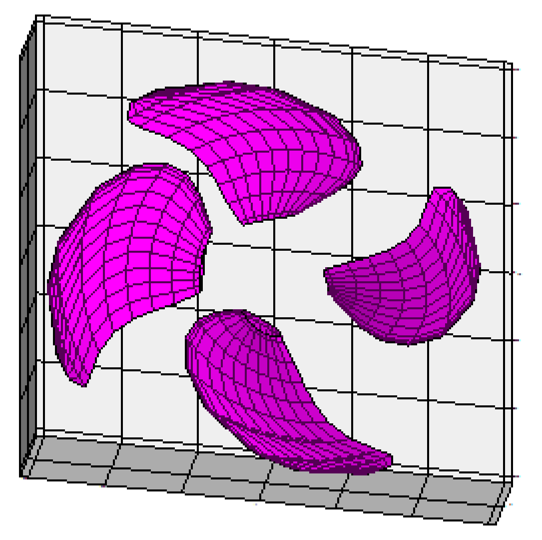
λ 30 cm model propeller

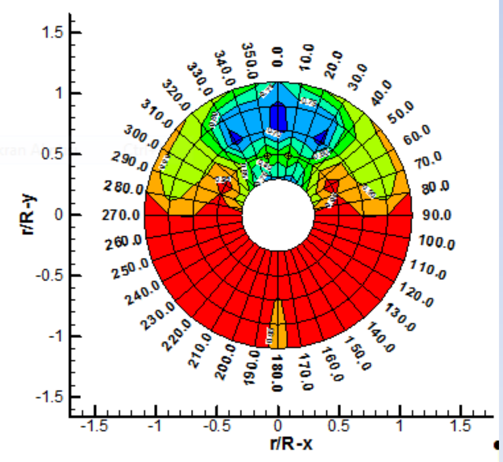
$$\Delta L_{(P)} = 20\log\left[1025.9\lambda^{3}\left(\frac{n_P}{n_M}\right)^{2}\right] dB$$

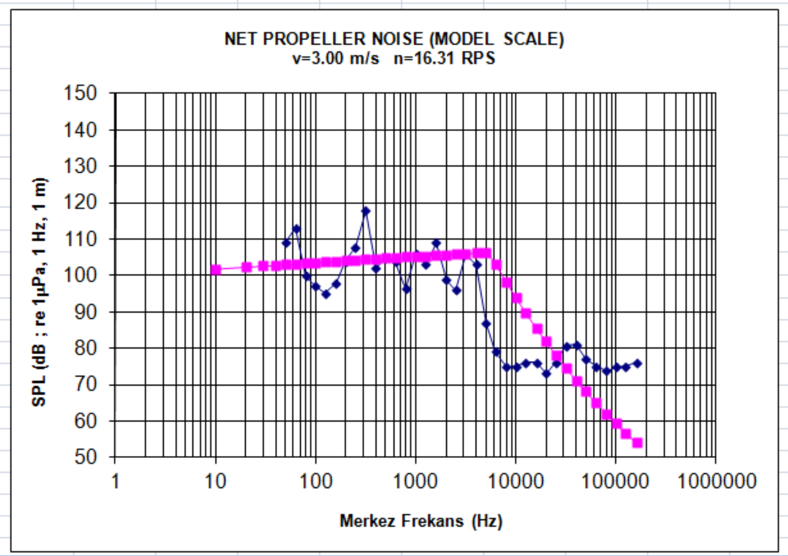
Numerical Example

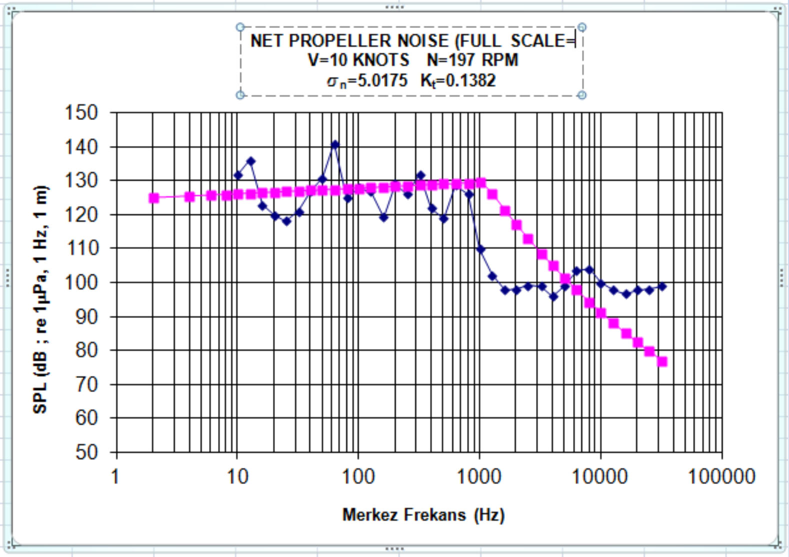


Number of Blades	-	4
Propeller Diameter (m)	-	2.100
Pitch Ratio at 0.7R	-	0.8464
Expanded Blade Area Ratio	-	0.55
Boss Ratio	-	0.276
Rake	-	0
Skewback (degrees)	-	40
Direction of Rotation	-	Right Handed






NET PROPELLER NOISE (MODEL SCALE)
v=3.00 m/s n=16.31 RPS
SPL (dB ; re 1µPa, 1 Hz, 1 m)
150
140
130
120
110
100
90
80
70
60
50
1
10
100
1000
10000
100000
1000000
Merkez Frekans (Hz)


NET PROPELLER NOISE (FULL SCALE=
V=10 KNOTS N=197 RPM
σ_n=5.0175 K_t=0.1382
SPL (dB ; re 1µPa, 1 Hz, 1 m)
150
140
130
120
110
100
90
80
70
60
50
1
10
100
1000
10000
100000
Merkez Frekans (Hz)

Part II: Modulation

- As propeller blade rotates about shaft axis it passes through different regions of wake flow
- This results in cyclical peaks in cavitation and cavitation noise level i.e. *noise envelope*
- Cyclical cavitation noise envelope may be observed at shaft rate f_{shaft} and its harmonic frequencies
- Cavitation noise spectrum is combined with cavitation noise envelope using amplitude modulation (Lourens, Kummert, Nielsen)
- Referred to as "DEMON" modulation

- Steady state broadband noise spectrum X(f) from Part I is converted to time domain signal x(t) using Discrete Fourier Transform

$$x(n) = DFT\{ X_r(k) \} \ \text{Pa}$$

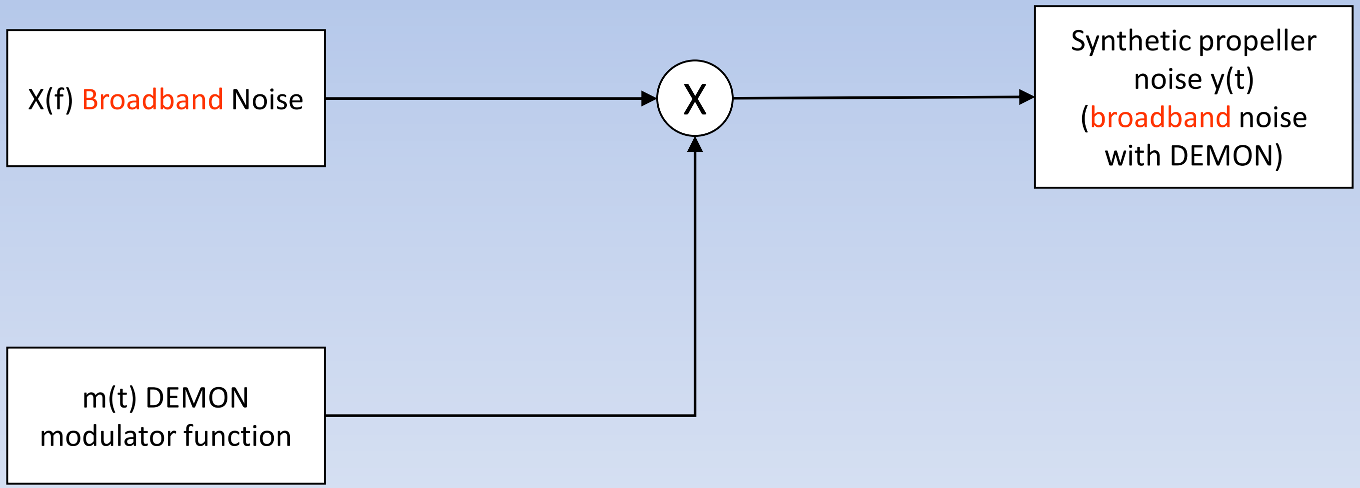
- “DEMON” modulator function m(t) is sum of cosine functions at frequencies f_{shaft} and multiples of f_{shaft}
- Weighting of frequency components given by parameters A_0, A_1, A_2,...

$$m(t) = \sum_{n=0}^{\infty} A_n \cos(n\,2\pi f_{shaft}\,t)$$

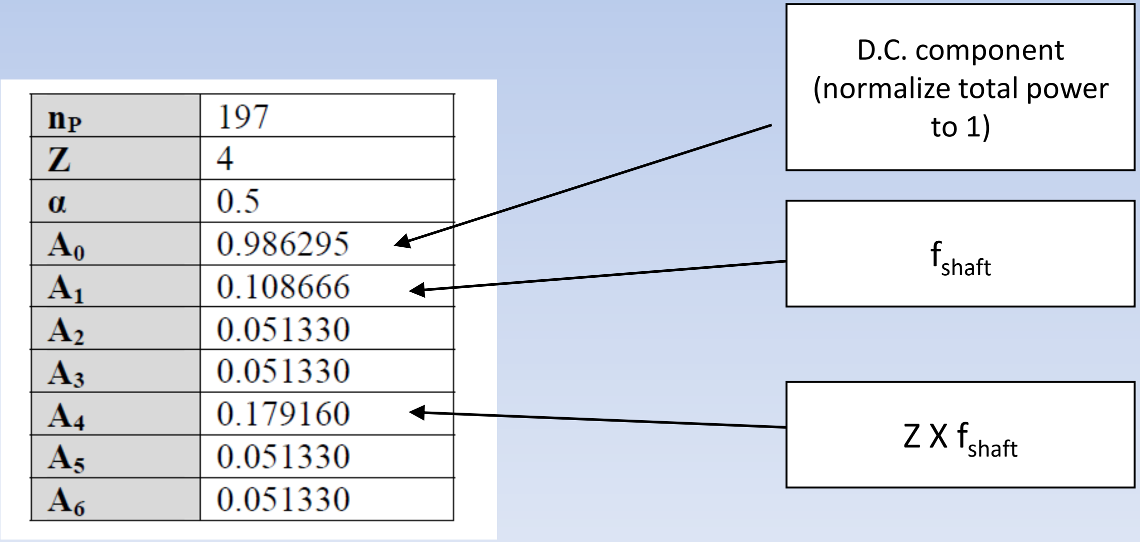
$$f_{shaft} = n_P / 60$$

- Steady state broadband noise is amplitude modulated with modulator function resulting in output propeller noise signal y(t)

$$y(n) = m(n/f_s)\cdot x(n) \quad \text{Pa}$$



- Setting coefficients of modulator function A_0, A_1, A_2, ... based on empirical experience
- Civilian ship propellers exhibit high level of DEMON frequencies at f_{shaft} X Z and f_{shaft}
- Military ship propellers exhibit only at f_{shaft} X Z



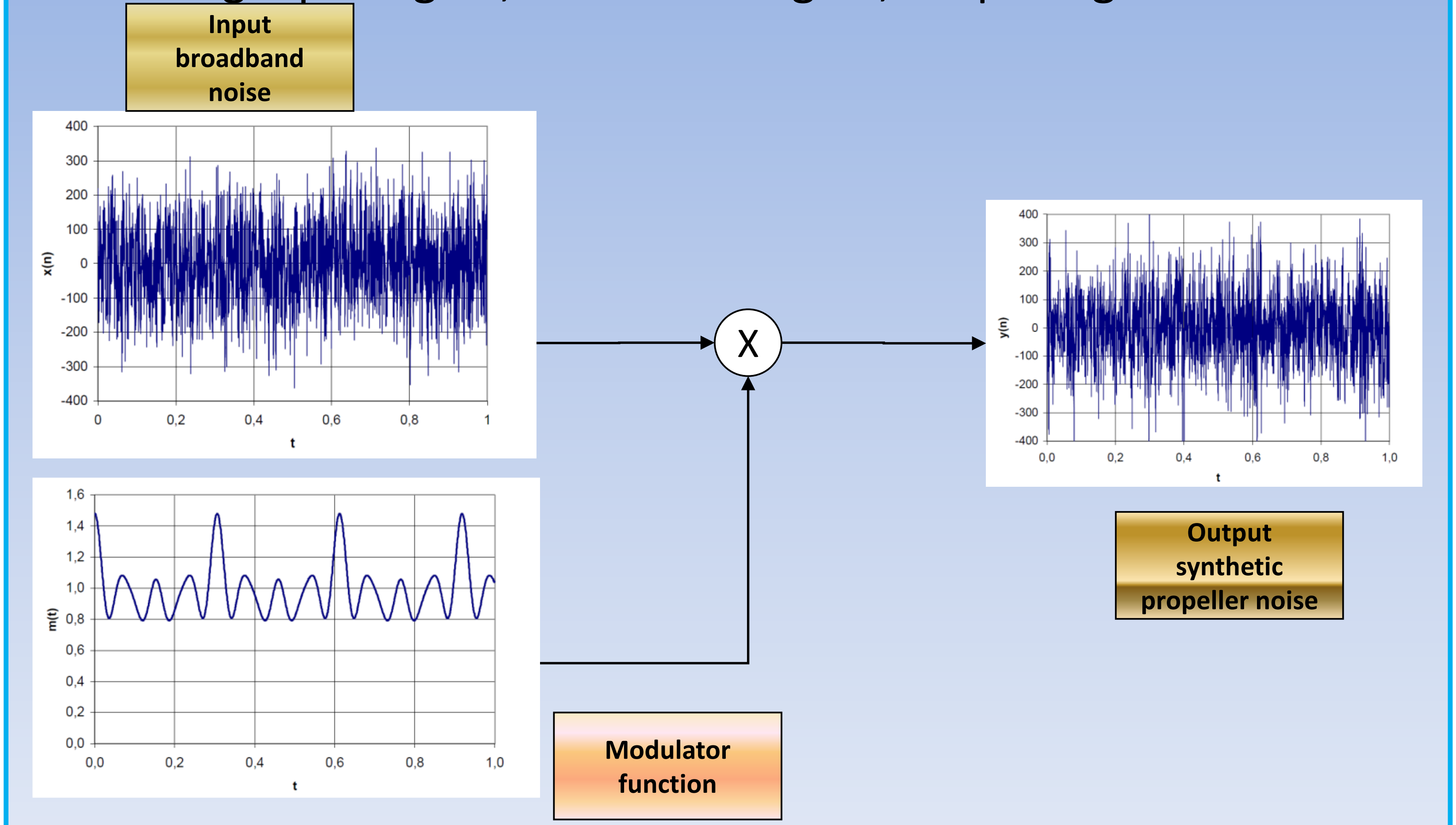
n_P	197
Z	4
α	0.5
A_0	0.986295
A_1	0.108666
A_2	0.051330
A_3	0.051330
A_4	0.179160
A_5	0.051330
A_6	0.051330

D.C. component (normalize total power to 1)

f_{shaft}

Z X f_{shaft}

- Resulting input signal, modulator signal, output signal



Input broadband noise

Output synthetic propeller noise

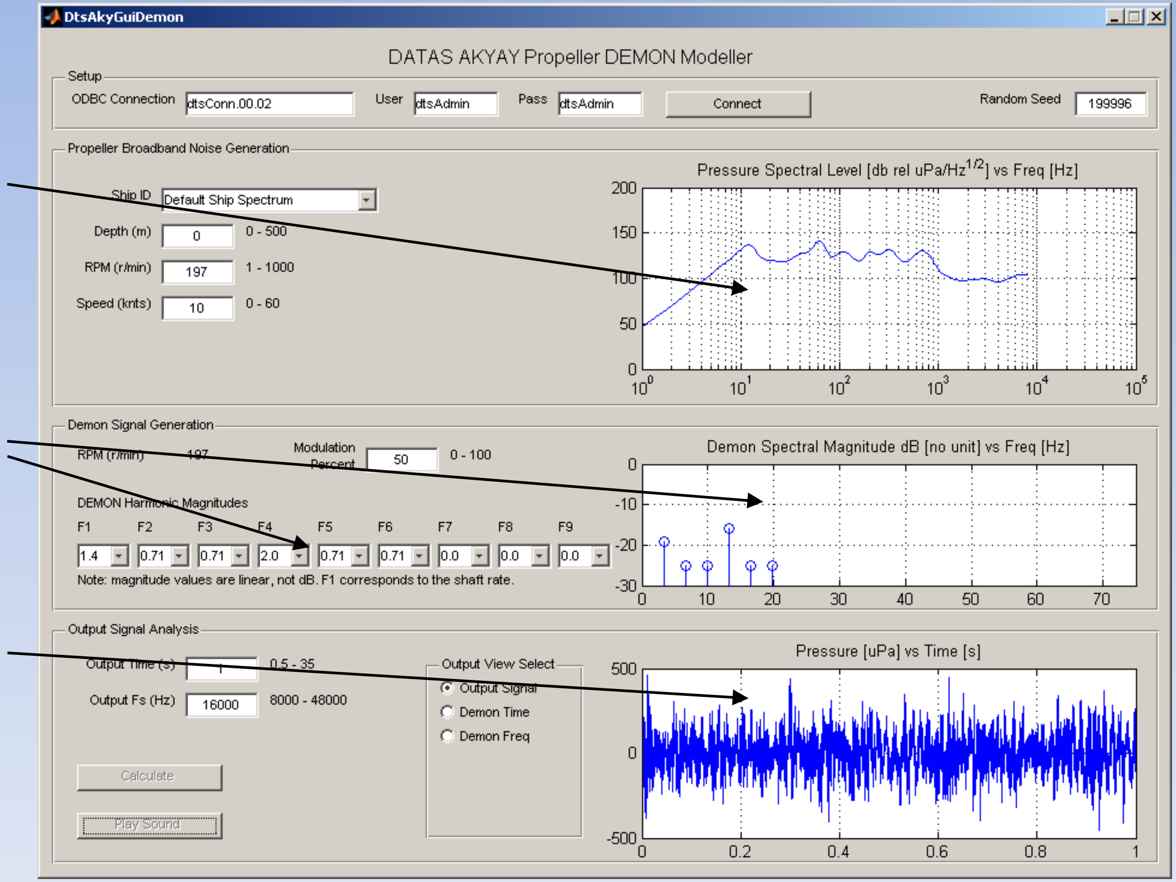
Modulator function

- DEMON modulator tool (MATLAB) graphical and WAV output

Input broadband noise

DEMON freq components A1, A2, ...

Output synthetic propeller noise



DtsAkyGuiDemon

DATAS AKYAY Propeller DEMON Modeller

Setup

ODBC Connection: dtsConn.00.02
User: dtsAdmin
Pass: dtsAdmin
Random Seed: 199996

Propeller Broadband Noise Generation

Ship ID: Default Ship Spectrum
Depth (m): 0 (0 - 500)
RPM (r/min): 197 (1 - 1000)
Speed (knts): 10 (0 - 60)

Pressure Spectral Level [db rel uPa/Hz$^{1/2}$] vs Freq [Hz]

Demon Signal Generation

RPM (r/min): 197
Modulation Percent: 50 (0 - 100)

DEMON Harmonic Magnitudes

F1	F2	F3	F4	F5	F6	F7	F8	F9
1.4	0.71	0.71	2.0	0.71	0.71	0.0	0.0	0.0

Note: magnitude values are linear, not dB. F1 corresponds to the shaft rate.

Demon Spectral Magnitude dB [no unit] vs Freq [Hz]

Output Signal Analysis

Output Time (s): 1 (0.5 - 35)
Output Fs (Hz): 16000 (8000 - 48000)

Output View Select
● Output Signal
○ Demon Time
○ Demon Freq

Pressure [uPa] vs Time [s]

Conclusions

- Emprical formula should be developed using more experimental data. (for Part I)
- More empirical study of real propeller noises to develop a database of DEMON parameters (for Part II)
- Synthetic propeller noise model may also include tonal frequency components produced by propeller geometry (especially for high shaft rates)